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Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
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Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal,* should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

Among papers to appear in forthcoming issues of the *Journal* are the following:

Stages of textural maturity in sedimentary rocks. By Robert L. Folk.

Depth of disturbance of sand on sea beaches by waves. By C. A. M. King.

Pre-Cambrian sinuous mud cracks from Idaho and Montana. By Harry E. Wheeler and James J. Quinlan.

Playa sediments of Rosamond Dry Lake, California. By Warren B. Hamilton.

The sediments of Lake Elsinore, Riverside County, California. By John F. Mann, Jr.

Grain orientation in sands and sandstones. By W. Schwarzacher.

A rapid substitute for textural analysis. By Irving Sherman.

Derivation of a size-frequency curve from the cumulative curve, By James Bush.

Some remarks on the mineral epidote in connection with the loess problem. By F. F. F. E. van Rummelen.

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FIGS. 1–11, JUNE, 1951

OCCURRENCE AND LITHOLOGIC ASSOCIATIONS OF EVAPORITES IN THE UNITED STATES[1]

W. C. KRUMBEIN
Northwestern University, Evanston, Illinois

ABSTRACT

Subsurface and outcrop data on evaporites were compiled on maps showing their geographic distribution in geologic systems within the United States. The wealth of data currently available shows that evaporites are more common and widespread than is generally recognized. They are present in all Paleozoic and later systems excepting possibly the Cambrian.

The evaporite occurrences are classified into four common lithologic aspects. These include marine sediments above and below the evaporites, transitions from red beds to normal marine above or below, and evaporites entirely within a red bed sequence. Some aspects occur typically in intracratonic basins, and others on shelf areas. The lithologic associations within the evaporite section are also divisible into four groups, from which inferences may be derived regarding environmental and tectonic conditions of origin.

INTRODUCTION

An extensive literature is available on evaporites, covering their occurrence, conditions of deposition, and vertical and lateral relations to associated sediments. Many papers describe evaporites in specific areas or within limited parts of the stratigraphic column. In addition, numerous well records, unpublished in detail, show evaporites in parts of the sections penetrated. These data show that evaporites occur in rocks of every system from Ordovician through Tertiary.

The classical textbook approach, which emphasizes early occurrence of evaporites in the Silurian, and widespread occurrence in the Permian, is too general in the light of abundant subsurface data now available. Evaporites are much more common and widespread than could be determined from standard textbooks available to students.

The present paper is a by-product of regional sedimentary-stratigraphic studies carried on at Northwestern University. As the regional data were compiled, it became clear that interesting implications were raised by the changing picture of evaporite occurrence through time. The writer is not aware that these numerous occurrences have been compiled into a systematic presentation of the geographic distribution of evaporites by geologic periods, associations with other sediments, or relations to contemporaneous tectonic frameworks.

The purpose of this paper is to present maps of evaporite occurrence arranged into lithologic associations for each geologic period. The paleogeography and lithologic associations are also discussed in terms of environmental and tectonic conditions prevalent during evaporite deposition. The treatment is confined to evaporites of restricted marine occurrence. Deposits of salt lakes, soda lakes, playa lakes, or secondary gypsite are not included. In some instances the available data are not clear on exact origin, and doubtlessly some marine deposits were overlooked or misinterpreted.

The factual data were obtained from a variety of sources, too numerous to cite in every instance. Several general references (Adams, 1904; Phalen, 1919; Stone, 1920; Alling, 1928) supplied much data on economic deposits of gypsum and salt. Dr. H. G. Hershey of the Iowa Geological Survey kindly made available information on evaporite occurrences in that state. Mr. R. T. Hazzard of the Gulf Refining Corp., Shreveport, La., reviewed portions of the manuscript re-

[1] Paper presented at Chicago meeting of S.E.P.M., April 27, 1950.

lating to Gulf Coast evaporites. The writer is also indebted to his colleagues at Northwestern University, especially Dr. L. L. Sloss, for much aid in assembling evaporite occurrences.

VERTICAL RELATIONS OF EVAPORITES

Examination of numerous published sections, well logs and cuttings, and field observations in selected areas, shows that evaporites occur in several vertical successions or aspects. A common aspect includes normal marine sediments above and below the evaporites. Another common vertical relation ranges from marine beds below the evaporites to red beds above. An inverted form of this second succession ranges from red beds below evaporites to normal marine beds above. Finally, evaporites may occur entirely within red bed sequences.

Within this broad framework of four common aspects are many local variants. Moreover, the occurrence of unconformities within or closely associated with the evaporite sections introduces unknown factors in the original succession of deposits. Despite these complexities, it is instructive to examine the broad regional distribution of evaporites on the basis of the four aspects. In a sense, the areal distribution of these aspects represents the distribution of evaporite facies.

Figure 1 shows four generalized stratigraphic sections illustrating the four evaporite aspects. In these diagrams only gross features are included. The evaporite section in any of the columns may include gypsum, anhydrite, salt, primary dolomite, limestone, green, red, or black shale, and variable amounts of sandstone. The normal marine section is usually composed of limestone or dolomite, but may include marine shale or thin sandstone. The red bed sections include mainly red, brown, and variegated shale, with red, gray, or white sandstone.

The first column of figure 1, with marine beds above and below the evaporite section, is typical of Ordovician evaporites in the Williston Basin, Silurian evaporites in the Williston and Michigan Basins, Devoinan evaporites in the Williston, Iowa, and Michigan Basins, Mississippian evaporites in the Michigan and Illinois Basins, and Cretaceous evaporites in Florida.

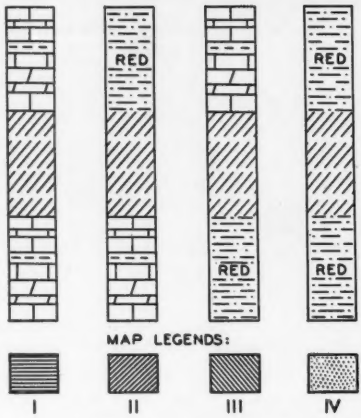

FIG. 1.—Generalized stratigraphic sections showing four broad aspects of evaporite occurrence. The legends below the columns apply to figs. 2–11, inclusive.

The second column of figure 1 shows evaporites transitional from marine beds below to red beds above. This over-all aspect is characteristic of Mississippian evaporites in central Montana, Amsden-Minnelusa evaporites in the Black Hills, and Jurassic and Cretaceous evaporites in parts of the Gulf Coast region.

The third column in figure 1 shows evaporites transitional from red beds below to marine beds above. The Silurian evaporites in New York, Pennsylvanian evaporites in the Paradox Basin, the Permian of east central New Mexico, some Jurassic evaporites in south central Montana, and some Cretaceous evaporites in Florida belong to this category.

The fourth column of figure 1 shows evaporites interbedded above and below with red beds. Some Devonian and Mississippian evaporites of southwestern Montana, Permian evaporites in Kansas, Oklahoma, and the Black Hills, and

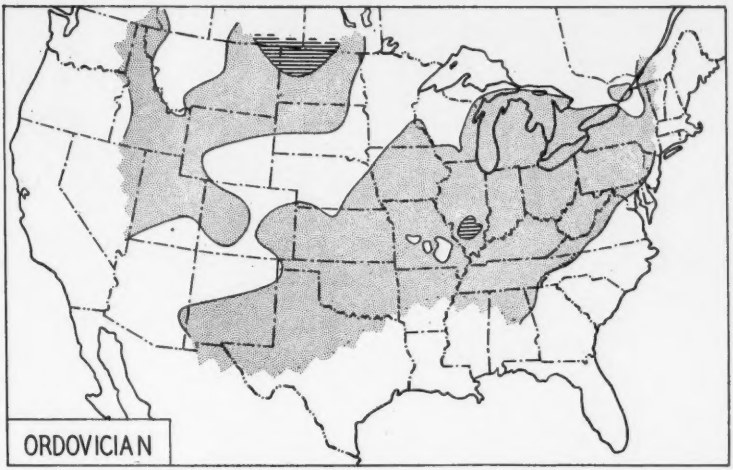

FIG. 2.—Map of Ordovician evaporites. The present extent of Ordovician rocks is indicated by the gray overprint.

Triassic evaporites of eastern Wyoming show these relations.

In referring to the occurrence of evaporites in various basins, the writer implies only their geographic location in the present structural basins. The tectonic implications of the basins, in terms of subsidence during deposition, are developed more specifically for each period in later paragraphs.

The occurrences cited, and many others, were compiled into maps showing the areal distribution of evaporites for each geologic period. Patterns distinguish areas having one or another of the four evaporite aspects. These maps are shown as figures 2 to 11. In each map the present extent of rocks of the system is also represented.

EVAPORITE DISTRIBUTION BY GEOLOGIC PERIOD

Ordovician Evaporites

Ordovician rocks have wide areal distribution in the United States (fig. 2), and evaporites occur in the Williston and Illinois Basins. In the former they are interbedded in the Whitewood-Bighorn dolomite, and the typical occurrence is 25 feet or less of anhydrite. In the Illinois Basin 25 to 50 feet of gypsum or anhydrite occur interbedded with the Joachim dolomite (Bays, 1945, DuBois, 1945).

The Ordovician evaporites are believed to represent deposition under environmental restrictions in a mildly subsiding intracratonic basin, surrounded by more normal open-circulation epicontinental sea conditions. No biohermal control for the evaporite areas is known to the writer.

Silurian Evaporites

Silurian rocks are less widespread in their present distribution than Ordovician rocks, but several important areas of evaporites are known. Table 1 shows the stratigraphic occurrence of the evaporites in each of the main areas in figure 3. The Silurian evaporites occur mainly in the cratonic portions of the United States, and represent intracratonic basin deposition in the Williston and Michigan Basins. Eastward from the Michigan basin the evaporites thin, and apparently

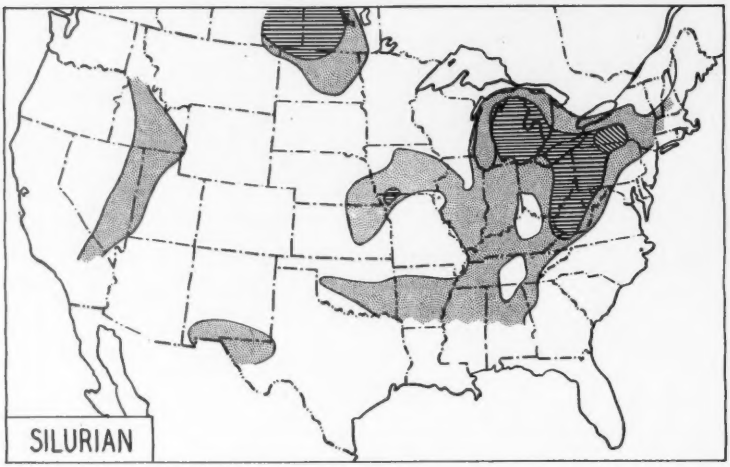

FIG. 3.—Map of Silurian evaporites.

represent shelf deposits in part, grading into thicker possible miogeosynclinal phases in Pennsylvania and West Virginia.

The occurrence of Vernon red beds below the evaporites in New York suggests continental deposits succeeded by restricted marine conditions with evaporites, culminating in the more open marine conditions of later Camillus time. In the more cental parts of the United States the relation of evaporites to normal marine limestone and dolomite implies restrictions in widespread epicontinental seas. In Michigan the environmental control appears to have been imposed by the biohermal ring around the basin. No reefs have been reported in the Williston Basin as far as the writer is aware, but reefs occur along the Silurian outcrops in Manitoba.

There is some question regarding the

TABLE 1.—*Silurian Evaporites*[1]

Area	Formation or Interval	Type of Association	Thickness of Evaporite Section, ft.	Kind of Evaporites
Williston Basin	Niagaran	I	25	anhydrite
Iowa-Missouri	Niagaran-Cayugan?	I	100	anhydrite
Michigan Basin	Bass Island Salina	I	3,000	anhydrite, salt
New York	Camillus Syracuse	III	500	anhydrite, salt
West Virginia	Salina	I	800	anhydrite

[1] In this and succeeding tables, the thickness of the evaporite sections is approximate and includes interbedded non-evaporites. Likewise, the column on kinds of evaporites emphasizes the prevalence of sulphates or chlorides, rather than differentiating sharply between anhydrite and gypsum.

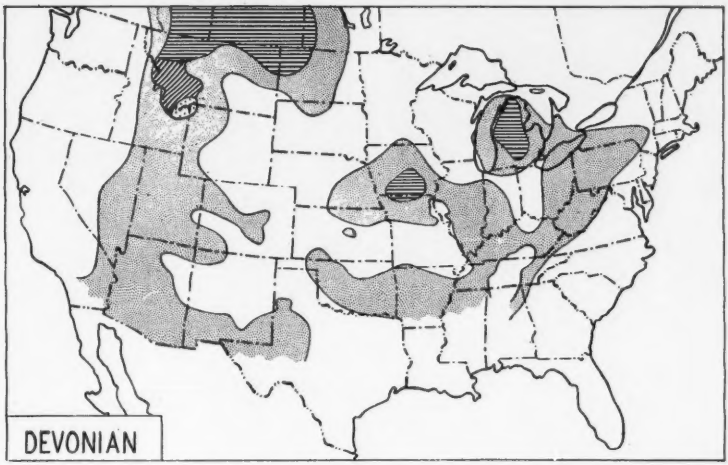

FIG. 4.—Map of Devonian evaporites.

occurrence of Silurian evaporites in Missouri and Iowa. The small area shown on the map is based on unpublished data, but there is a possibility that the evaporites may be of Devonian age. According to the Iowa State Geological Survey[1] there are no Silurian evaporites in Iowa. The map area, therefore, is considered to be tentative rather than established.

Devonian Evaporites

Three main areas of Devonian evaporites are shown in figure 4, and the stratigraphic data are listed in table 2. In northern Montana and southern Alberta, the evaporites have typical intracratonic basin characteristics, with some reef control, as shown by the Leduc reefs farther north in Alberta. To the northeast in Manitoba and Saskatchewan, evaporites occur in Middle Devonian rocks. In southwestern Montana the evaporites are wholly Upper Devonian. This section changes southward from anhydrite interbedded with marine dolomite to an evaporite-red bed section in the Three Forks. This gradation suggests approach toward a shore phase in southwestern Montana.

The Iowa evaporites occur interbedded with marine dolomite. The full areal

[1] H. G. Hershey, personal communication.

TABLE 2.—*Devonian evaporites*

Area	Formation or Interval	Type or Association	Thickness of Evaporite Section, ft.	Kind of Evaporites
Williston Basin	Potlatch Jefferson	I	400	anhydrite
Iowa	Cedar Valley-Wapsipinicon	I	50	anhydrite
Michigan Basin	Detroit River	I	1,200	salt
Southwest Montana	Three Forks	II, IV	50	anhydrite

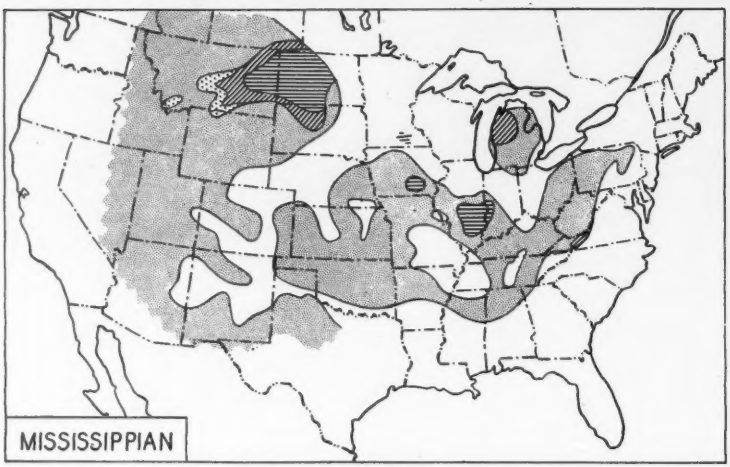

FIG. 5.—Map of Mississippian evaporites.

extent of the evaporites is not known to the writer, but the presence of collapse and solution breccia along the Wapsipinicon outcrop may imply fairly widespread original occurrence. No reef control of these evaporites is known to the writer, although at least one Devonian reef has been reported along the Devonian outcrop in Iowa.

In the Michigan Basin the evaporites are typical intracratonic deposits, interbedded with limestone and dolomite. Reefs are known in the Michigan Devonian outcrops, and it is not unlikely that some biohermal control of the restricted environment may have occurred during evaporite deposition.

Mississippian Evaporites

Five areas of evaporite occurrence during the Mississippian are shown in figure 5, and the stratigraphic relations are given in table 3. In the Williston Basin the evaporites grade westward from marine intracratonic basin facies through transitional shelf types toward

TABLE 3.—*Mississippian evaporites*

Area	Formation or Interval	Type of Association	Thickness of Evaporite Section, ft.	Kind of Evaporites
Williston Basin	Otter Charles	I	1,000	anhydrite
Southwest Montana	Kibbey	II, IV	100	anhydrite
Iowa	Keokuk	I	30	anhydrite
Illinois Basin	St. Louis	I	200	anhydrite
Michigan Basin	Michigan	II	350	salt
West Virginia	Maccrady	II	1,000?	salt, anhydrite, gypsum

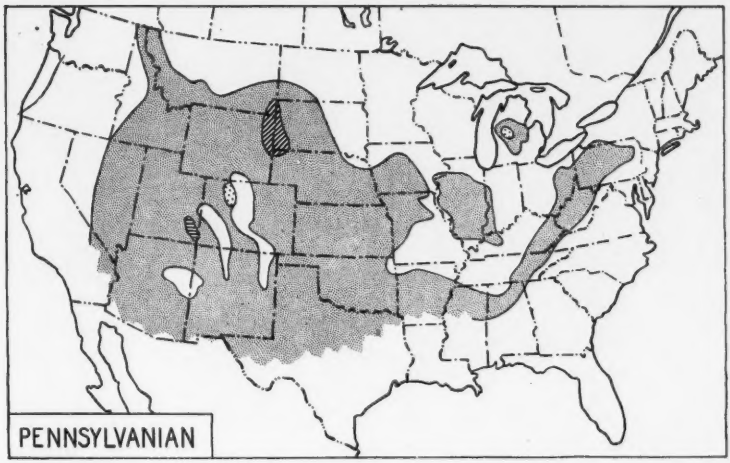

FIG. 6.—Map of Pennsylvanian evaporites.

sea margin deposits. The marine beds associated with the evaporites in the eastern part of the basin include normal marine limestone, dolomite, and green to black marine shale.

In Iowa the Mississippian evaporites are thin, and are interbedded with normal marine limestone. These suggest shelf or mild intracratonic basin conditions. The Illinois Basin evaporites occur interbedded with normal marine limestone, oolitic limestone, and they have typical intracratonic basin characteristics.

The evaporites in the Michigan Basin occur in a marine succession which includes limestone, green shale, and some sandstone above and below (Marshall and Bayport). In Virginia the evaporite succession of salt and anhydrite is less known to the writer. It is believed, however, to represent miogeosynclinal conditions.

As far as is known to the writer, none of the Mississippian evaporites show evidence of biohermal control of the restricted evaporite environments.

Pennsylvanian Evaporites

Data on Pennsylvanian evaporites are less detailed regarding correlation or stratigraphic position than are evapo-

TABLE 4.—*Pennsylvanian evaporites*

Area	Formation or Interval	Type of Association	Thickness of Evaporite Section, ft.	Kind of Evaporites
Paradox Basin, Utah	Paradox	I	4,000	gypsum, anhydrite, salt
Gypsum Basin, Colorado	Maroon	IV	500+	gypsum, anhydrite
Black Hills region	Minnelusa	II	50	gypsum, anhydrite
Michigan Basin	Virgilian?	IV	50+	gypsum

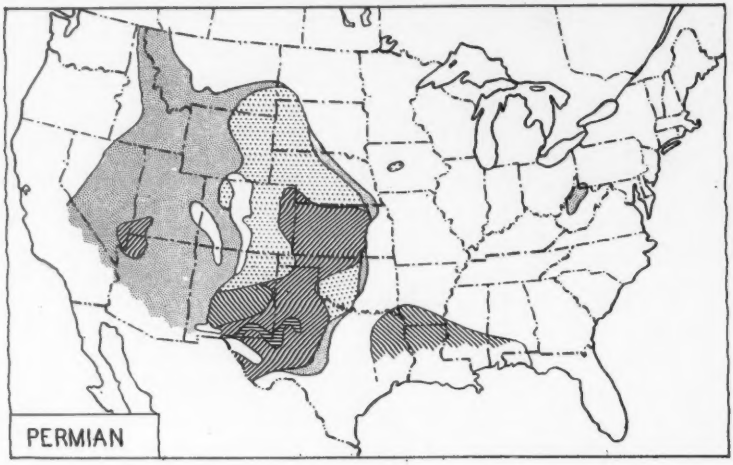

FIG. 7.—Map of Permian evaporites.

rites of earlier periods. Figure 6 shows four areas of occurrence, summarized in table 4.

The best known Pennsylvanian evaporites occur in the Paradox Basin of southeastern Utah, where they are associated with dark marine shale. The Gypsum Basin of north central Colorado has evaporites in the Maroon formation, interpreted as Pennsylvanian and Permian. The evaporites occur in a thick red bed section.

The relatively thin evaporites of the Black Hills region occur in the Minnelusa, associated with marine sediments and red beds. Some of these evaporites may be of Mississippian age. The evaporites of the Michigan Basin are correlated as possible Virgilian deposits, although some workers consider them to be Permian. It seems more likely that these evaporites represent the closing stages of intracratonic basin deposition, associated with an influx of clastic material, in contrast to the more typical marine limestone and dolomite of previous periods.

It is apparent that the Pennsylvanian evaporite aspects differ markedly from those of earlier geologic periods. The high content of clastics in Pennsylvanian rocks as opposed to carbonate rocks of earlier periods, tends to develop marine associations with shale rather than limestone, and apparently includes some aspects with typical continental or brackish red beds. The black shale of the Paradox Basin also poses a problem in the apparent association of evaporites with euxinic black shale.

In terms of tectonic control, it would appear that all the Pennsylvanian evaporites are related to unstable conditions during deposition, with marked subsidence in the Paradox and Gypsum Basins, and lesser subsidence in the Black Hills and Michigan Basin areas.

Permian Evaporites

The Permian Period was a time of very widespread occurrence of evaporites, as shown in figure 7 and table 5. Evaporites occur in all major subdivisions of Permian rocks, and this factor renders it difficult to show the detailed relations of evaporites on a single map for the entire period.

The greatest occurrence of evaporites

TABLE 5.—*Permian evaporites*

Area	Formation or Interval	Type of Association	Thickness of Evaporite Section, ft.	Kind of Evaporites
Black Hills	Minnekahta Opeche	IV	100	anhydrite, gypsum
Gypsum Basin, Colorado	Maroon	IV	500	anhydrite, gypsum
Grand Canyon area	Kaibab Toroweap	II	900	anhydrite, gypsum, salt
Northern N. Mexico	San Andres	IV	100	anhydrite
S. Central N. Mexico	Yeso Abo	III	2,000	anhydrite, salt
SE. New Mexico	Rustler Salado	II	2,000	anhydrite, salt, polyhalite
Central Texas	San Angelo Clear Fork Wichita	II	1,500	anhydrite, gypsum
Texas Panhandle	Pease River Clear Fork Wichita	II	2,000	anhydrite, gypsum
Oklahoma Panhandle	Dog Creek Blaine Cimarron	IV	1,000	anhydrite, gypsum
SW. Oklahoma	Blaine Clear Fork Wichita	IV	1,500	anhydrite, gypsum, salt
W. Central Kansas	Harper Wellington Marion	II	800	anhydrite, gypsum, salt
Iowa	Leonardian?	IV	50	gypsum
Gulf Coast	Louann Werner	III	1,500±	salt, anhydrite

is in the New Mexico-West Texas-Midcontinent region. Leonardian evaporites occur on the shelf area of southeastern New Mexico and the Texas panhandle, in part related to red beds. By Guadalupian time the evaporites spread southward to part of the Central Basin Platform, and Ochoan evaporites occupy large parts of the Delaware Basin.

In the Midcontinent area, Leonardian evaporites occur above the Wolfcampian limestone of Kansas, but farther north, in Nebraska and Wyoming, the evaporites are entirely within a red bed sequence. The western edge of important evaporites in Wyoming coincides with the development of Phosphoria (Embar) marine sediments farther west.

The Kaibab-Toroweap evaporites of the Grand Canyon area occur in a mixed limestone-red bed association. The evaporites in the Gypsum Basin of north central Colorado are assigned in part to the Permian. A small area of evaporites in Iowa is assigned to the Permian, although the stratigraphic relations are

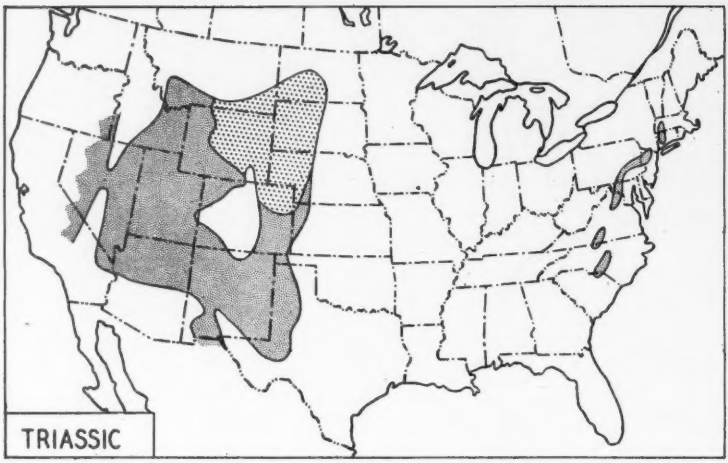

FIG. 8.—Map of Triassic evaporites.

not entirely clear. The large area of evaporites in the Gulf Coast is based on the Permian correlation of the Louann salt and Werner anhydrite. This evaporite occurrence represents the special case of an unconformity at the top of the Louann salt. There is some question regarding the age of these evaporites, and the writer follows Hazzard, Spooner, and Blanpied (1947). (See, however, Imlay, 1943.)

Permian evaporites represent a variety of conditions in their deposition, from intracratonic basin occurrences to widespread shelf deposits. Biohermal trends occur along the edges of the Central Basin Platform of Texas, with restriction of environments in the Delaware and Midland Basins. However, the basin deposits are more typically euxinic shale than evaporites (except in the Ochoan of the Delaware Basin), and most Permian evaporites are back-reef shelf facies. King (1942) presents a series of lithofacies maps which clearly show the relations during several stages of the Permian. Hills (1942) reconstructed the paleogeography of the Permian seas in Texas and the Midcontinent. Adams and Frenzel (1950) more recently discussed the relation of evaporites to the Capitan Reef.

Triassic Evaporites

Triassic evaporites occur mainly in the Chugwater and equivalents of eastern Wyoming, Nebraska, and the Dakotas. In thickness the evaporite-bearing section may exceed several hundred feet. Gypsum and anhydrite, in a red bed sequence, are the typical occurrences.

Triassic deposits are widespread in the Rocky Mountain area, as shown in figure 8. Evaporite occurrences other than those in the Chugwater, however, are subordinate and may represent postdepositional selenite development, as far as the writer's knowledge extends. The Chugwater red beds with their enclosed evaporites appear to represent deposition on an unstable shelf area, resulting from restricted marine invasions moving eastward from the triassic sea farther west.

Jurassic Evaporites

Jurassic evaporites cover several extensive areas, as shown in figure 9, sum-

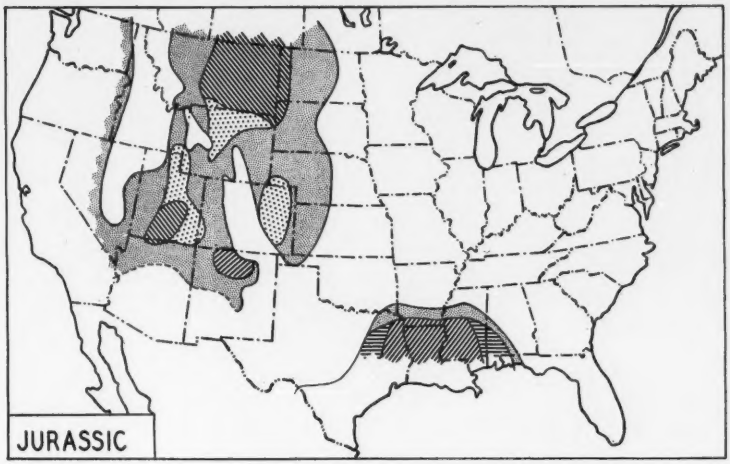

FIG. 9.—Map of Jurassic evaporites.

marized in table 6. The Gypsum Spring formation and equivalents have widespread occurrence in Montana and Wyoming, ranging in aspect in a southerly direction from type III (red beds below the evaporites and limestone above) to type IV (red beds above and below).

Jurassic salt occurs in southeastern Idaho, in the Preuss sandstone, and apparently extends southward into Utah,

TABLE 6.—*Jurassic evaporites*

Area	Formation or Interval	Type of Association	Thickness of Evaporite Section, ft.	Kind of Evaporites
Central Wyoming	Gypsum Springs	IV	200	anhydrite, gypsum
Central Montana	Gypsum Springs	III	100	anhydrite, gypsum
SE. Idaho	Preuss	IV	450	gypsum, salt
Central Utah	Arapien	IV	1,000?	salt
S. Central Utah	Carmel	III, IV	400	anhydrite
N. Central N. Mexico	Todilto	II	100	anhydrite
E. Central Colorado	Summerville equivalent	IV	200	anhydrite, gypsum
Southern Arkansas	Buckner[1]	II	350	anhydrite
Northeast Texas	Buckner[1]	I	700±	anhydrite, salt
SW. Alabama	Buckner[1]	I	950	anhydrite, salt

[1] Buckner member of Haynesville formation.

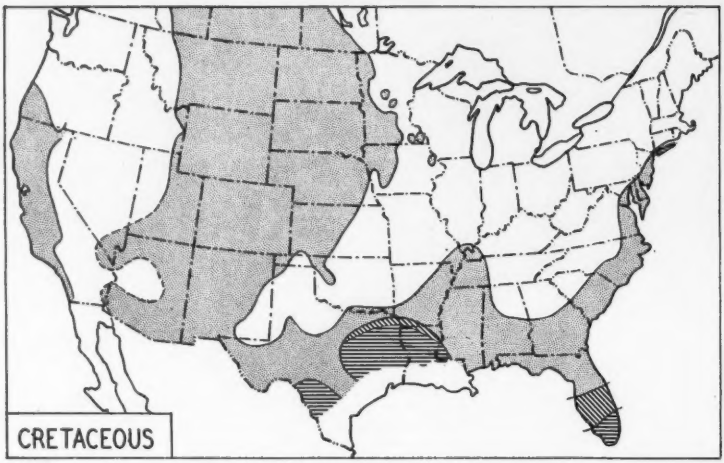

FIG. 10.—Map of Cretaceous evaporites.

possibly originally extending as far as the area of Carmel evaporites in the south-central part of the state. A smaller area of Todilto evaporites occurs in northern New Mexico, in an association ranging from limestone below anhydrite to red beds above (Mansfield, 1927; Baker, Dane, and Reeside, 1936).

The fairly extensive evaporites in eastern Colorado are in the Summerville equivalent. The anhydrite section is interbedded with variegated shales, and may contain some limestone. It is tentatively assigned to type IV occurrence. Imlay (1949) includes maps of the Jurassic facies, from which figure 9 was taken in large part.

In the Gulf Coast area evaporites are extensive in the Buckner member of the Haynesville formation, where the dominant anhydrite section, with a prominent salt bed, attains a thickness of at least 900 feet. The Buckner lies above the Smackover limestone. If the Louann salt and Werner anhydrite are Jurassic, the Jurassic would include two evaporite sequences separated by the thick Smackover limestone section.

Cretaceous Evaporites

Cretaceous evaporites are confined to the Gulf Coast area, where they extend essentially from southwestern Texas to the tip of Florida. All are in Lower

TABLE 7.—*Cretaceous evaporites*

Area	Formation or Interval	Type of Association	Thickness of Evaporite Section, ft.	Kind of Evaporites
NW. Louisiana	Ferry Lake	I	300±	anhydrite
SW. Texas	Fredericksburg	I	150	anhydrite, salt
S. Central Florida	Comanchean	III	6,000	anhydrite
Southeastern Florida	Comanchean	I	4,000+	anhydrite, salt

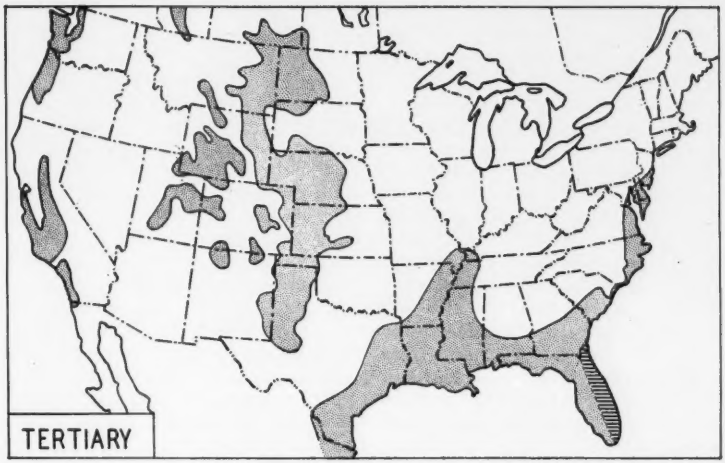

FIG. 11.—Map of Tertiary evaporites.

Cretaceous rocks. The stratigraphic occurrences are listed in table 7 and the areal distribution of the evaporites is shown in figure 10.

In the upper Gulf Coast area, evaporites occur in the Ferry Lake, with showings of gypsum and evaporitic dolomite on the outcrop near Austin, and in northeast Texas and southwestern Arkansas. In the subsurface the anhydrite occurs in a limestone section, assigned to type I. In northwestern Louisiana evaporites occur in the Ferry Lake and Rodessa, ranging through interbedded anhydrite, shale, and thin limestone to red beds near the top of the section.

In Florida the Cretaceous evaporite section ranges to a thickness of 6,000 feet in Dade County, where the undifferentiated Comanchean shows numerous anhydrite zones interbedded with limestone and some dolomite. In Highland County, Florida, interbedded anhydrite and limestone overlie a red bed section some 400 feet thick.

Tertiary Evaporites

Evaporites of Paleocene and Eocene Age occur in Florida, associated with dominantly marine limestone. In general, the evaporites occur in the eastern half of the state, as suggested in figure 11. The writer does not know the full areal extent of the evaporites, nor their stratigraphic details. The evaporite section apparently is of the order of several hundred feet thick.

Tertiary evaporites of lacustrine origin are relatively widespread in parts of the Rocky Mountain area, such as the Green River formation of southern Wyoming (Bradley, 1948). Numerous occurrences of Quaternary evaporites in soda lakes, playas, and other situations are also known. Many occurrences are described by Phalen (1919) and Stone (1920). These are not shown on figure 11, nor are they considered in this paper which is confined to evaporites of restricted marine origin.

ORIGIN OF EVAPORITES

A voluminous literature has developed on the origin of evaporites, and a number of references on the subject are included at the end of this paper. It is generally agreed that anhydrite, gypsum, and salt, with associated evaporitic lime-

stone and dolomite, and minor amounts of potassium salts, represent evaporation of sea water under restricted environmental conditions.

Most writers follow Grabau (1913, 1920) in grouping general conditions for marine evaporite occurrence into marginal salt pans, salinas, lagoons, and relict seas. Of these, the first two appear to be minor, and most interpretations involve restricted lagoons or relict seas.

Restrictions of the environment may be caused by biological, physiographic, or tectonic controls. Rings of reefs may form along the edges of subsiding basins, producing enclosed lagoons separated from the open sea except through narrow inlets. Barrier reefs may develop landward lagoons with similar restrictions, giving rise to back-reef evaporites (King, 1942; Adams and Frenzel, 1950). Restricted lagoons may also be developed by barrier beaches, which interpose a physiographic control. Arms of the open sea, slightly deeper than fronting offshore waters, may be left behind as relict seas during regression of the strand line. In some instances tectonism may isolate the central portion of a subsiding basin, and develop restricted circulation.

Under arid conditions, with excessive evaporation, the restricted environment may attain salinity greater than that of the open sea. Excessive evaporation produces a lowering of water level and induces a permanent inflowing current of normal sea water through the inlets among the barriers.

Maintenance of inflow from the open sea provides a continuous supply of dissolved salts, and a balance may be reached between evaporation and inflow for given conditions. Inevitably, concentration of salts in the restricted area is increased, and may reach the saturation point for some. The sequence of salts deposited is a complex response to physico-chemical conditions involving temperature, pressure, relative solubilities, pH of the solution, and other factors. Lateral as well as vertical variations and transitions may occur among the precipitated salts (Adams and Frenzle, 1950).

Lang (1937) visualized the seas of the Permian Basin as broad epicontinental seas connected with the normal marine sea to the southwest. High evaporation in the partially enclosed portions of the seas induced a current toward the evaporating portions and developed zones of increasing salinity. Along the shore zone proper, however, a band of brackish water could develop from reduction of the salinity by tributary terrestrial drainage. Evidence for the zoning is presented by the varying character of the sediments and evaporites deposited in each.

This approach, differing somewhat from the concept of a strictly relict sea separated from the open ocean by a physical barrier, affords opportunity for movement of continuous supplies of normal sea water into the evaporating area. The theory explains more satisfactorily than some others the accumulation of thick evaporite sections showing progressive lateral gradations over their area of occurrence. Hills (1942) followed Lang and showed that the paleogeography of the Permian bears out the thesis that different degrees of salinity were simultaneously present.

Some evaporite sections suggest the observed sequence of salts obtained by evaporation of sea water (Clarke, 1924), but more commonly the evaporites occur in cyclical sequences of certain dominant evaporites (Kroenlein, 1939; Roth, 1942). The cycles may contain gypsum, anhydrite, salt, dense dolomite and limestone, and they may have interbeds of clay shale or other clastics deposited between episodes of evaporite formation. In many instances a single evaporite, such as anhydrite, attains considerable thickness and areal extent.

Cyclical occurrences of evaporites may be explained by recurrent dilution of the water, washing in of clastics, seasonal changes, or by local or temporary removal of restrictions. Thick beds of a

single evaporite may be referred to transport and winnowing of precipitated evaporites within a basin of accumulation. Through this process anhydrite crystals, for example, may be moved toward the center of a subsiding basin by currents in the saturated medium, forming a thick deposit of nearly pure anhydrite. Branson's hypothesis of multiple basins (1915) also provides a means of segregating the evaporites. Evaporation and crystallization may proceed to a given stage in one basin, with the concentrated solution then flowing to another basin where a succeeding salt is deposited. The great thickness, purity, and areal extent of the Louann salt in the Gulf Coast area have been attributed to this process by Hazzard, Spooner, and Blanpied (1947).

The four broad aspects of evaporites described in this paper can be related to certain general conditions of environment and tectonism. The first group, interbedded with normal marine sediments above and below, occurs typically in intracratonic basins, as shown by its distribution on the maps, supplemented by data on thickness and other features of the deposits. In thinner sequences this group may also occur on shelf areas, in more widespread shallow restricted seas.

Intracratonic basin occurrences of the type I evaporite aspect appear to be related to major cycles of deposition, in which the evaporites represent a late stage in the cycle from basal clastics through normal marine deposits, into evaporite sequences, and with a return to normal marine conditions in the final stages (Sloss, 1950). Tectonic control of the depositional cycles may operate indirectly by establishing optimum conditions for reef growth along tectonic hinge lines, or it may operate directly by isolating lagoons or relict seas within the central part of an intracratonic basin. Similarly, lagoons or relict seas may be developed on unstable shelf areas by tectonic control.

The second and third type of evaporite occurrences, in which normal marine beds are found either above or below the evaporites, are typically on the shelfward margins of intracratonic basins, and possibly along the cratonward edges of miogeosynclines. In part, the evaporites represent intermediate stages of major depositional cycles in which either the basal beds or the topmost beds are dominantly brackish to nonmarine clastic deposits. Back-reef evaporites are commonly in the second or third group, as are occasional broad shelf occurrences of thin evaporitic sequences. Restricted back-reef lagoonal environments, sometimes of great areal extent, were common at times in the Permian (Adams and Frenzel, 1950).

The fourth aspect of evaporites, with red beds above and below, is most typically a shelf occurrence, deposited in widespread restricted lagoons, relict seas, or zones of varying salinity, alternating with brackish or nonmarine clastic sediments. The Chugwater of Wyoming is an example. In some instances, as in the Pennsylvanian-Permian of the Gypsum Basin in Colorado, this aspect may represent intracratonic basin conditions with dominant nonmarine clastics, and alternating restricted marine invasions supplying the evaporites.

The maps of evaporite occurrence show certain systematic patterns which repeat themselves through time. In early and middle Paleozoic the evaporites were formed characteristically within intracratonic basins, as type I, and they recur in the same areas during succeeding periods. This repetition suggests a recurring pattern of intracratonic basin sedimentation, with occasional cycles during which one or another basin may have been inactive, or not subject to restriction, as during the Silurian in the Illinois area. The smaller areas of early and middle Paleozoic evaporites associated with red beds may be largely a reflection of subsequent removal by erosion of widespread but thinner shelf deposits.

It was not until the Permian that widespread shelf type evaporites occur

interbedded with red beds. During the Triassic this type dominates, but in the Jurassic Period some evaporites are again associated with more normal marine deposits in the western Jurassic seas. During Jurassic and Cretaceous the Gulf Coast area became the main site of marine-derived evaporite deposition, presumably under intracratonic basin conditions with marginal red bed phases. If the Louann salt and Werner anhydrite are Permian, this trend toward subsidence and restriction extends back at least to late Paleozoic.

LITHOLOGIC ASSOCIATIONS WITHIN EVAPORITE SECTIONS

The preceding discussion treated the evaporite-bearing succession as a whole, in terms of its relation to other sedimentary groups above and below. In this sense the over-all aspect of the sections could be expressed in terms of its areal variation on the map. Such maps are facies maps, and the distribution of the evaporite facies led to the inference that evaporites are formed on shelf areas, within intracratonic basins, and perhaps in miogeosynclines. These inferences are further supported by a study of the sediments associated and interbedded with the evaporites themselves. In this more detailed sense the sediments within the evaporite section form a lithologic association consisting of evaporites, detrital sediments, and carbonate rocks.

The writer has been able to recognize four lithologic associations within evaporite sections. These specific lithologic associations are characterized by the kinds of sandstone, shale, and limestone or dolomite which are found interbedded with the anhydrite, gypsum, or salt section. From these associated sediments, plus data on thickness of the section, it is believed that the tectonic conditions of deposition may be inferred. In all instances the evaporites themselves represent the kinds of restricted environmental conditions previously mentioned, but the associated sediments may range from nonmarine to neritic open-circulation deposits.

Table 8 lists four evaporite lithologic associations, their occurrence in terms of the four broad aspects shown on the maps, and a summary of inferred tectono-environmental conditions under which they were deposited. The red bed-quartzose sandstone-evaporite association is characterized by quartzose sheet sands interbedded with red bed shales, anhydrite, gypsum, and thin evaporitic dolomite. The sheets of quartzose sandstone imply relatively slow deposition on broad stable shelf areas, with perhaps some wind work involved. The red unfossiliferous shale suggests brackish or freshwater environments, and the interspersed beds of anhydrite and thin densely crystalline dolomite imply recurrent short-lived marine invasions and the development of restrictions either in relict seas or under marginal phases of the gradational conditions suggested by Lang (1937). Parts of the Leonardian of south central Kansas are characteristic of this lithologic association.

The red bed-subgraywacke sandstone-evaporite lithologic association is similar to the preceding type, except that, in general, the section is somewhat thicker, the sandstones are more lenticular, and the red bed shale is dominantly silty or sandy. Usually also, the evaporites occur in thicker beds, and may form a greater proportion of the whole section than in quartzose sand associations. These features suggest deposition under much the same environmental conditions, but with greater instability of the depositional site. In thick successions the subgraywacke lithologic association implies deposition in intracratonic basins, whereas relatively thinner successions appear to be characteristic of unstable shelf areas. The subgraywacke association occurs in parts of the Chugwater of eastern Wyoming, which apparently represented an unstable shelf. The Maroon beds of the Gypsum Basin are interpreted as an intracratonic basin occurrence.

TABLE 8.—*Lithologic associations of evaporites*

Association	Aspects	Inferred Conditions of Origin
Red bed-quartzose sandstone-evaporite	IV (II, III)	Stable shelf; continental-transitional environments, with minor marine restricted.
Red bed-subgraywacke sandstone-evaporite	IV (II, III)	Mildly unstable shelf; continental-transitional environments, with minor marine restricted.
Marine shale-carbonate-evaporite	I, II, III	Mildly to moderately unstable shelf or intracratonic basin; shallow marine, in part restricted.
Carbonate-evaporite	I, II, III	Mildly to moderately unstable shelf or intracratonic basin, possibly miogeosynclinal; shallow marine, in part restricted.

Both the quartzose sandstone and subgraywacke evaporite associations are characteristic of group IV of the broader evaporite facies shown on the maps. They may, however, occur in groups II and III, especially in the parts of the section which grade vertically from or into lower or higher red beds.

The marine shale-carbonate-evaporite lithologic association represents a more seaward expression of the shelf conditions, with a higher proportion of relatively thin limestone or dolomite, and with detrital sediments represented by shales with marine faunas. In some instances thickened successions of this kind, with relatively more shale than carbonate, occur in intracratonic basins. The interbedded evaporites and dark shales of the Paradox Basin are an example. Examples of more typical shelf occurrences are found in the Leonardian of central Texas.

The carbonate-evaporite lithologic association is most characteristic of intracratonic basin deposition, as in the Williston, Iowa, and Michigan Basins during parts of the Paleozoic Era. This lithologic association may also extend from the basin across adjoining shelf areas to the miogeosynclinal margin, as they appear to do in the Silurian from Michigan southeastward. The carbonate-evaporite association would appear to require relatively widespread seas, restricted within basins by reef rings or tectonically-imposed barriers. In shelf occurrences this association may represent one or more phases of Lang's zonal distribution of shallow epicontinental seas.

It is noteworthy that the writer has been unable to find examples of red bed-arkose-evaporite lithologic associations. The presence of wedge arkose, as in the Fountain formation along the Front Range, and in Pennsylvanian deposits along the southern rim of the Anadarko Basin, imply rapid erosion of a granitic terrain and correspondingly rapid burial in a nearby yoked basin. The general absence of interbedded evaporites may mean that the rapid filling of the subsiding area allowed no time for development and evaporation of lagoons or relict seas. Perhaps more likely, the development of red soil on interfluves and the stripping of fresh feldspar from stream channels in a humid tropical source area (Krynine, 1949) supplied enough stream runoff to more than balance evaporation in associated seas and lagoons.

CONCLUDING REMARKS

A principal purpose of this paper is to show that evaporites of marine origin are relatively common sediments in the geologic column. The writer has no doubt that he overlooked many addi-

tional occurrences, and he may have included some evaporites of nonmarine origin. References on evaporites cite many occurrences of salt and gypsum in which the relations to surrounding sediments are not clear. As far as possible the writer culled out instances in which the gypsum or other evaporite appeared to be secondary material concentrated by ground water, disseminated as crystals in shale or other sediments, or formed as gypsite crusts on the surface. Undoubtedly some of these were misinterpreted, which suggests that evaporites of marine origin are probably even more common than the maps indicate.

The widespread and recurrent deposition of evaporites during essentially all parts of the Paleozoic and later eras suggests that conditions favoring excessive evaporation of sea water occurred in many parts of the United States on many occasions. The lateral gradations of the evaporites into normal marine deposits in many instances, implies that large parts of the continent had normal climatic conditions simultaneously with the formation of evaporites in restricted areas. Hence, there seems no need for calling upon "general aridity" during a geologic period to account for its evaporites. Rather, the implication for historical geology is that tectono-environmental conditions for evaporites were of common occurrence, and that the evaporites fit into the climatic picture of any period as normally expected phenomena.

It seems evident from the data available that evaporites and their specific lithologic associations represent deposits which cut across elements of the tectonic framework. As such, they may show characteristically different relations on shelves, in intracratonic basins, and in miogeosynclines. In common with other kinds of sediments which similarly transect the tectonic framework, such as red beds themselves, black shale, and cyclothems, the interpretation of the sections may be colored in part by the conditions under which they are found. When studied in terms of their areal patterns of occurrence, however, they display broad patterns of uniformity or systematic gradation which relate them to corresponding aspects of environmental and tectonic control.

As far as the writer is able to determine, evaporites are rare or absent among typical eugeosynclinal deposits. They apparently may occur in miogeosynclines, but their most typical development appears to be cratonic. On the craton the basin type evaporites are volumetrically the most important.

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A NEW SEDIMENTARY PETROLOGICAL INTERPRETATION OF THE RESULTS REPORTED BY THE SWEDISH "ALBATROSS" DEEP-SEA EXPEDITION—1947-1948

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ABSTRACT

A new affirmation is given for the existence of recent dolomite layers in the sediment of tropical seas and oceans. It is not always possible to determine the thickness of the non-indurated sediment from geophysical data when they are obtained in either cold or warm waters.

Under what circumstances does a sediment which remains in the third stage of induration become a rock?

One of the results of the *Albatross* expedition was that the explosion echoes indicated considerably great values for the thickness of the sediment layers in the Atlantic Ocean (up to 3660 m) and in the Tyrrhen Sea (up to 2700 m). In the Indian and Pacific Oceans, however, the sediment layers are found to be less than 300 m. This latter is probably due to submarine eruptions of which the intercepting lava beds reflect the explosion waves. (After H. Pettersson, 1949.)

During the coring work, the coring tubes were damaged repeatedly when hard lava bottom was reached after pushing through the paradiagenetical sediment. The longest cores brought up by the expedition were nearly 21 m. The supposition that the reflection of the explosion waves is due to intermediate lava beds has not yet been proven, but is only one of several acceptable explanations, as will be discussed below.

It is already possible to recognize various stages of the induration of the sediment by deformation phenomena (Weynschenk, 1949, chap. II, table III, figs. 4–5; table IV, fig. 6; table V, fig. 8). Sander (1936, pp. 86–89, fig. 46) mentioned the non-indurated sediment as a sediment in a stage of "paradiagenese," which is translated into para-induration. The process of para-induration is divided into three stages of consolidation, sometimes also called paradiagenetical stages. Sedimentary petrological investigations were made by the present author on a Jurassic coastal breccia; here allothigenic rock particles are embedded in a calcareous sediment. Thus, chemical reactions could be observed in the paradiagenetical sediment where, in proportion to the several paradiagenetical stages, the chemical processes in the sediment differ. Or in other words, the chemical processes during para-induration change because they have to keep step with the steady advancing process of para-induration and its resulting stages of consolidation, which continually causes other physical circumstances. Also, the chemical reactions in the sediment as related to allothigenic rock particles already indurated, were studied.

Future investigations in this direction will indicate more details concerning chemical reactions during para-induration, by means of deformation phenomena studied on thin- and polished-sections.

However, returning to our theme, the following admissible facts can cause reflection waves:

1) Intermediate lava beds at all possible depths and places where submarine eruptions took place.

2) Biogenic layers, especially coral reefs and also algal reefs, submerged by tectonic movements and later covered

by sediment.

3) Large diffused silicified bodies in a paradiagenetical sediment may have reached their complete induration into rock in consequence of the chemical reaction in those certain regions, but the calcareous paradiagenetical sediment surrounding the cherts may not yet be impregnated, and may still remain in the third stage of consolidation. Such a relationship means that even hundreds of meters of paradiagenetical sediment may exist under these cherts.

4) Also, dolomite layers, which originated in the sediment during paraindura-tion, may have a base consisting of sediment in the third stage of consolidation.

Explosion waves are surely reflected from cherts and, also, from the innumerable dolomite crystal-masses of the dolomite layers in the sediments of the tropical oceans and seas. It is most interesting to note that the reflection waves in the warm Indian and Pacific Oceans are due to layers situated at depths of less than 300 m. In the article of Weynschenk (1951) concerning the dolomite problem, the author explains the existence of dolomites of large mass and extent in the sediment of tropical oceans and seas from a few hundred meters depth to greater depths. The low values of the explosion echoes from the *Albatross* are almost certainly caused by the dolomite layers and, as such, is a new affirmation for this.

It is very unlikely that at so many different places in the Indian and Pacific Oceans so many intermediate lava beds would exist at depths less than 300 m! Such a relationship would indicate a period of young world-wide submarine eruptions, of which nothing is known.

Only the best founded reasons are mentioned above and they indicate the necessity of being very careful in making conclusions from reflected waves, regarding the thickness of the paradiagenetical sediment carpet.

Another and last question is how to deal with the finishing stage of the induration process, when the paradiagenetical sediment becomes a rock. Is it even possible for a calcareous sediment to become a limestone as long as the sediment remains constantly under water? According to the very thick paradiagenetical sediment layers—up to 3660 m—in the Atlantic Ocean, an indication, indeed, is given that a calcareous rock almost surely does not originate under a constant water cover, although a confirmative answer cannot be given as yet.

I should like to propose that the future geophysical deep-sea research must be correlated with sedimentary petrological data.

If in the future we wish to avoid confusion in nomenclature of the succession of the induration of the sediment, it would be advisable for geophysicists or deep-sea scientists not to use a nomenclature of their own which is more or less useless in practical sedimentary petrology. For instance, when by exploring the deep sea an expedition should report a "loose" sediment of hundreds of meters thickness in some sea, the word "loose" is unfortunate. You can call slime or dregs a loose sediment as long as it can flow. When flow is no longer possible, the sediment is no longer a "loose" sediment, but then in any case we have to do with a paradiagenetical sediment. "Loose" sediments of hundreds of meters thickness do not exist sensu stricto.

In connection with a remark by one of my colleagues, I would further point out that the sedimentary petrological experience of B. Sander, W. Schwarzacher, and the present writer, are, for the greater part, observations of sedimentation in shallow waters. Even if so, however, there is still no reason why such observations should not be applied to deep water research, as all sediments show chemical reactions and consolidation processes whether they are shallow or deep water sediments.

Only the first steps of this new method for future development in sedimentary petrology have been made.

It is hoped that more attention will be

paid to this new trend of sedimentary petrology which can give us so much inspiration even in questions concerning deep-sea research, as this paper has tried to show.

Included in the following list of references are the papers of Sander, of Schwarzacher, and of Weynschenk in which, for ecological statements, as to be seen in the micropaleontological papers also referred to, the cited trend can be of greatest help.

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PISOLITHS, OOLITHS AND CALCAREOUS GROWTHS IN LIMESTONE CAVES AT PORT CAMPBELL, VICTORIA, AUSTRALIA

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ABSTRACT

Cave pisoliths and ooliths, with other discrete calcareous growths of larger dimensions but comparable origin, from three caves in the limestones of the Port Campbell Beds, Heytesbury formation (Miocene), Victoria, have been formed under somewhat different conditions in the separate caves. The main variants concerned in their formation lie in (1) the characters of the cave floors, (2) the greater prevalence of clay in suspension and iron oxide in solution in the vadose waters issuing from parts of the roof of one cave (Pearce's), (3) the strength of air circulation, and (4) the presence of organic matter (algae) associated with bicarbonate pool waters in one cave (at London Bridge Beach). Both calcareous and ferruginous varieties of pisoliths and ooliths have been developed in these caves.

INTRODUCTION

Most of the caves known to occur at the base of the Miocene limestone cliffs in the Port Campbell district, south coast of Southwestern Victoria (Baker, 1943), are repeatedly attacked by the sea at the present time. Only three of these caves lie suitably placed beyond the range of frequent marine attack and are at the same time subject to the conditions requisite for cave pisolith and oolith formation. Certain conditions vary among the three caves, several conditions being also different from those prevalent in the small number of other pisolith- and oolith-bearing caves on record (Baker and Frostick, 1947).

Two of the caves containing pisoliths and ooliths occur in Loch Ard Gorge, 4½ miles east of Port Campbell township. They are Pearce's Cave at the head of the east arm of the gorge, and Carmichael's Cave situated near normal high tide mark on the west side of the gorge. The third cave is at the head of London Bridge Beach, 3½ miles west of Port Campbell township.

The bicarbonate-bearing solutions necessary for pisolith- and oolith-formation, are derived from the passage of vadose waters along joint and bedding planes in the relatively porous Miocene limestones and associated, richly calcareous clays of the area.

CONDITIONS WITHIN THE CAVES

Pearce's Cave

Owing to the existence of conditions more favorable to their development, pisoliths and ooliths are found in greater numbers in Pearce's Cave. This cave is also farthest from wave activity and is seldom, if ever, invaded by the sea at the present time. Even the highest storm waves observed here do not penetrate beyond the sandy floor at the cave entrance.

The cave entrance has an outer portal 15 feet high and 30 feet wide, with large pendant calcareous growths plastering the cliff walls above. Thirty-five feet from the outer portal, the dimensions of the cave diminish to form an inner portal 4 feet high and 20 feet wide. The floor of the cave to this point is partly sandy, partly rocky. Twenty-six feet beyond the inner portal, the cave enlarges to form a chamber 62 feet long, 45 feet wide, and ranges from 4 feet to 10 feet in height. The total length of the cave is 123 feet.

The floor of the cave is generally flat, with a slight rise towards the rear. The roof is also flat and approximately hori-

zontal, solution of a lime-rich bed having occurred along a prominent bedding plane in flat-lying Miocene strata.

A short underground stream, in a channel 2 to 3 feet wide and 3 to 4 feet deep, flows along the whole length of the cave on its eastern side. It carries the surface waters discharged into a sinkhole situated several hundred yards north-northeast of the landward end of the cave. The connection between the sinkhole and the cave is apparently along open joint and bedding planes. Near the point of issue of the underground stream from the cave mouth, occurs an unconsolidated deposit of pisolith-like bodies, largely ferruginous and resembling the buckshot gravel that is present on the surface of the clifftops in this vicinity, but containing considerable amounts of calcareous material. These have mostly been collected into the underground channel by periodic increases of seepage waters across the cave floor during wetter seasons, when the waters of the underground stream also overflowed the retaining walls of the channel.

Myriads of short, hollow tubular stalactites averaging 3 inches in length and one-quarter inch in diameter, are dependent from a white, carbonate encrusted roof possessing shawls along joint planes and occasional clusters of rather larger stalactites. Innumerable drips and streams of bicarbonate-charged water fall from the stalactites at rates with a general range of 1 to 214 drops per minute. Some, however, are as slow as one drop in 10 minutes and some even slower. Two or three of the feeder sources were running so fast as to form constant streams, beneath which no pisoliths were observed. Neither were pisoliths developed beneath some of the very slowly dripping feeders.

One pool, beneath a series of slow-dripping (one drop in 10 minutes) feeders was 56 inches long, 33 inches across, and partly infilled with mud (1½ inches depth of mud and 1½ inches of water). The only calcareous growths developed under these conditions are thin "spats" of calcium carbonate (pl. 2, B) encrusting the mud immediately beneath the drips. The mud represents residue from the dissolution of the limestone above the cave, and contains gelatinous iron hydroxide. It was carried by vadose waters along open joint and bedding planes to the cave. This is evidenced by the reddish-brown color of murky water in a fast-running feeder stream issuing from the roof near the rear of Pearce's Cave. Precipitation and deposition beneath this particular feeder has built up a cascade-structure composed of carbonate-cemented ferruginous clay. The structure so formed is mound-like and surmounted by a depression occupied by continuously overflowing murky water. By virtue of the existence of two other fast-flowing feeder sources of comparable character to the one described, parts of the cave floor in their vicinity are quite muddy and unsuitable for pisolith formation. Elsewhere, however, the cave floor is hardened with stalagmitic encrustations on which have grown numer-

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EXPLANATION OF PLATE 1

A—Round, smooth pisoliths (×3), from almost dried out pool in Pearce's Cave, showing cracks and small facets at points of contact where cementation had commenced.

B—Encrusted sub-spherical pisoliths (×1.7). Two on left from Carmichael's Cave, two on right from Pearce's Cave.

C—Pisoliths and ooliths (natural size) comprising most of the contents of one small pool on northwest side of Pearce's Cave; showing facetted forms developed by growth in a thickly populated pool. The smaller forms show a partial polish in parts, the largest forms have bisque surfaces.

D—Encrusted, elongated flat pisoliths (×1.7), with smoother areas on upper surface only, from almost stagnant pool in Pearce's Cave.

E—Bottom, top, and lateral aspects of lenticular pisoliths (×2), from surface of stalagmitic encrustation on floor towards rear of Pearce's Cave.

(Photographs by A. C. Frostick.)

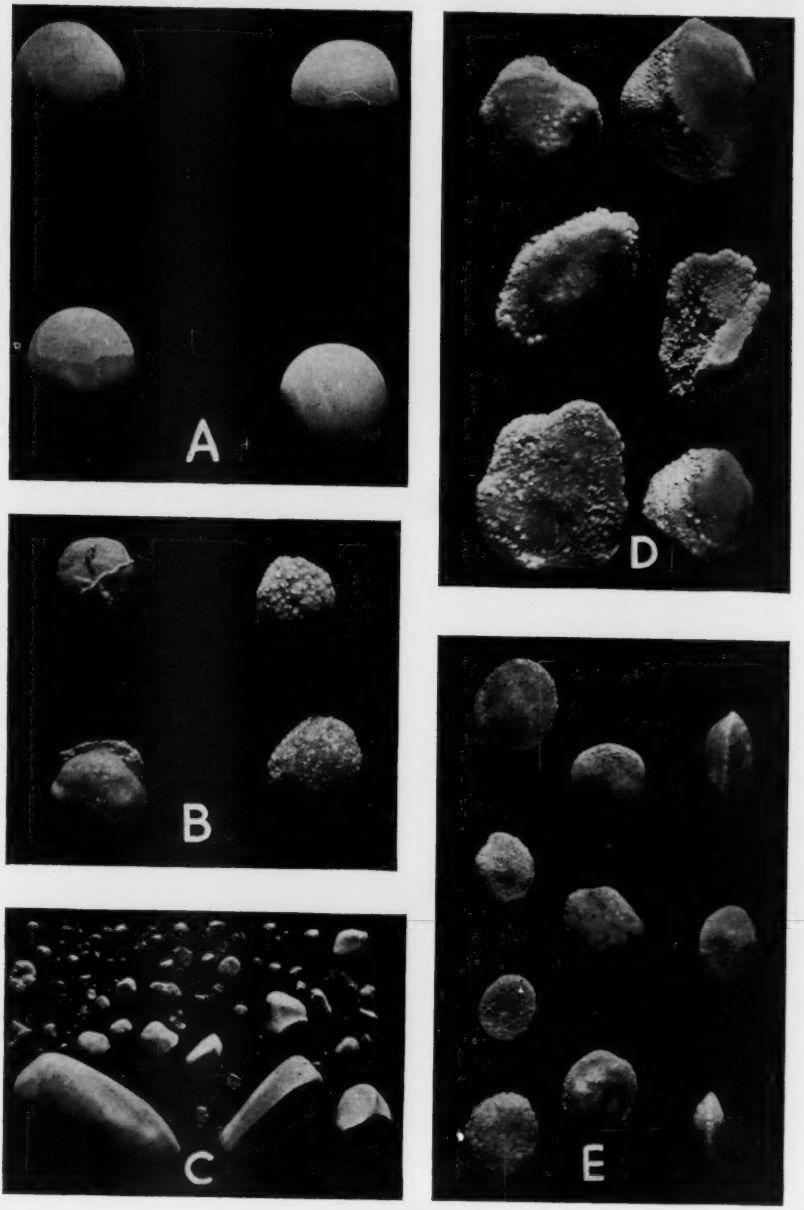

PLATE 1

ous, short, blunt stalagmites (pl. 3, A). The diameter of these stalagmites ranges from 1 to 10 inches and averages 3 to 4 inches. Their length ranges from 1 inch to 30 inches with an average of 3 inches. The summits of the majority of these stalagmites consist of smooth, flat, or slightly convex areas about 1½ inches in diameter. Small splash cups up to one-half an inch across occur at the center of these smooth areas in rare examples.

Rippled cascade-structures, forming mounds and ledges up to 2 feet in height, occupy parts of the floor at the back of the cave and near the cave walls. In a few places, stalagmites on the cascade-structures have united with stalactites, forming small pillars of compound character and up to 1½ feet long. Toward the rear of the cave, the growth of these stalagmitic structures has caused the height of the cave to dwindle to 3 feet and less.

On the cascade-like mounds and ledges, and in depressions between the small stalagmites on the stalagmitic encrustation forming parts of the cave floor, occur numerous pools and basins ranging in size from 1¼ inches to 4 feet across and containing bicarbonate waters in various states of agitation. The walls and floors of some of the pools and basins are smooth and gently undulating, being lined with calcium carbonate. Thin layers of $CaCO_3$ have grown in eave-like fashion from the margins across the water surface in several of the pools and basins. Snch growths indicate that greatest precipitation of $CaCO_3$ takes place at the water surface, where escape of CO_2 is accelerated when pool surface ripples generated by the impact of the feeders, impinge upon pool margins. Thin ledges of $CaCO_3$ with a banded character are consequently formed, their edges farthest from the sides of the pools and basins showing horizontal, radiating acicular crystals. Some of the ledges have grown for up to 9 inches from the sides toward the centers of the pools. A few pools were almost completely roofed over by these horizontal growths, more particularly where smaller pools are situated beneath a gentle overflow from the stalagmitic cascade-structures, thus indicating that the eave-like structures can be produced under the stimulus of rippling caused by the inflow of lateral seepage waters, as well as by rippling resulting from the impact of feeder drips. Where formed around stalagmites situated in depressions containing bicarbonate waters, ledge-growth has resulted in the development of "flanged islets" (pl. 3, A). Here, two types of $CaCO_3$ deposition are shown: (1) a relatively thin, compact, layered upper deposit, supporting (2) pendant crystal clumps. Growth was evidently initially laterally away from the stalagmite, thus building up the flange surface, but later reverted to vertical downward growth when a supporting layer (i.e. the flange surface) had been established.

The pisolith-bearing pools are characteristically without retaining mounds or lips. Small pools 1 inch by 1½ inches across, were full of pisoliths and ooliths. In one such pool, eight larger pisoliths occurred on top, and numerous smaller ones, accompanied by ooliths, occurred beneath (cf. pl. 1, C). Surrounding the pools, the stalagmitic crust is invariably smooth and clean of extraneous carbonate growths for a width of 1 inch from the

EXPLANATION OF PLATE 2

A—Irregular and sub-round forms of pisoliths (×2). Cave on London Bridge Beach.
B—"Spat" (×2.7)—a thin, concave calcareous disc formed on the surface of slime in mud-bearing pools in Pearce's Cave.
C—Slender elongated pisoliths (×1.7), from cave on London Bridge Beach.
D—Elongated pisoliths (×1.7), showing bean-like shapes and included fragment of partially shrivelled marram grass blade, from cave on London Bridge Beach.
E—Ferruginous pisoliths (×1.8) are nearly always irregular in shape and show partial polish, from underground stream in Pearce's Cave.

(Photographs by A. C. Frostick.)

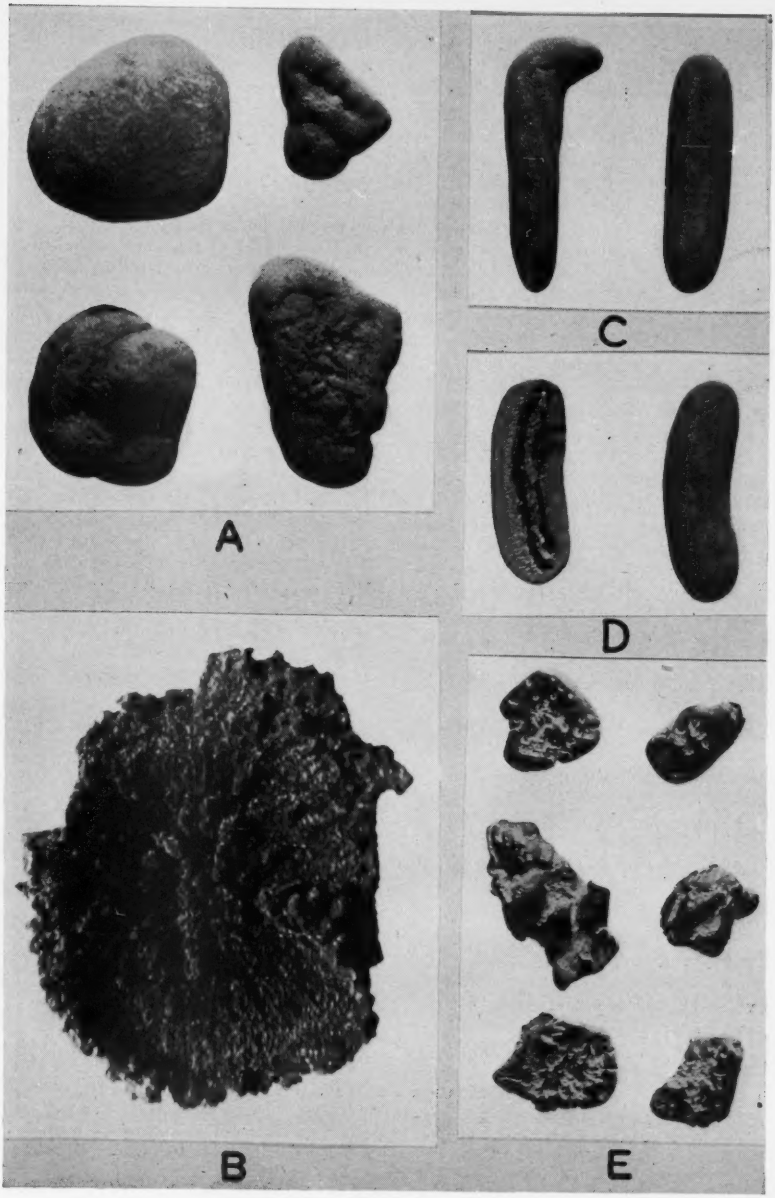

PLATE 2

edge of the pool water. Beyond this pisolith- and oolith-free zone, the crust is frequently rough-surfaced and littered with many loose and some attached pisoliths of small size, principally lenticular in shape (pl. 1, E). These constitute types that have grown by $CaCO_3$ deposition entirely from seepage and splash water, rather than in the confines of pool waters. The lenticular pisoliths invariably occur in place with their smoother surface upward and the rougher surface downward. Some parts of this stalagmitic crust are free of depressions, and yet are littered with lenticular pisoliths. In place of the pools, however, smooth, pisolith-free patches 1 inch to 1½ inches across, occur beneath the more persistent (although slowly dripping) feeders. The pisoliths here are thus formed within the range of splash and seepage waters, and not by direct drip, hence the probable explanation from the prominent generation of lenticular pisoliths in such parts. Many of these smooth, small patches are present where the calcareous crust on the cave floor is littered with a countless multitude of these lenticular pisoliths. The reason for the development of the small bare patches beneath some feeders, and small pools beneath others, is of interest. Perhaps these auxiliary feeders came into existence at a later stage in the development of the stalagmitic encrustation which, due to its slow rate of growth, has not had time for sufficient vertical extension necessary to show the form of the small pool (or splash cup). In other words, these small, smooth, bare patches may be the floors of future splash cups.

Conditions on the floor of Pearce's Cave have been much disturbed in places by the many visitors to the cave. This is evidenced where muddy portions of the cave floor have been considerably churned up, the depressions (footprints) serving to create artificial pools in which, however, pisoliths are seldom found. That conditions of pisolith growth have been upset in some of the pisolith-generating pools, is indicated by the frequent occurrence of carbonate-encrusted fragments of newspaper, some charred but some with the print still visible through a thin veneer of calcite. Elsewhere in the cave pools are pieces of cardboard and match sticks attached to the stalagmitic encrustation. Objects such as metal discs, glass fragments and the like have been placed in some of the pools to become "petrified." It is at the rear, less disturbed portion of the cave where roof height diminishes, that normal conditions are maintained and the pisoliths and ooliths are best developed.

Air circulation.—The atmosphere circulates at a low rate in Pearce's Cave. Smoke released at the rear of the cave, drifted toward the cave entrance at the rate of 0.15 ft./sec. The smoke moved along the floor of the cave, a clean-cut division occurring between smoke-laden and clear air about half way up from the floor.

Air temperatures.—Air temperatures in Pearce's Cave were measured in the summer season (January, 1946); the temperatures are listed in table 1.

TABLE 1.—*Air temperatures in Pearce's Cave*

Location	Temperature
Outside cave entrance	73°F.
At outer portal	73°F.
At inner portal	72°F.
In center of chamber	70°F.
At rear of cave	70°F.

Pool temperature.—The temperature of the pool waters taken (a) at the entrance, (b) in the center, and (c) at the rear of

EXPLANATION OF PLATE 3

A—"Flanged islet"—a short, blunt stalagmite with a flange of calcium carbonate deposited at water surface level in a shallow pool in Pearce's Cave. (approximately natural size)

B—Sand stalagmite from Carmichael's Cave, showing deep splash cup and cemented sand grains. (approximately natural size)

(Photographs by A. C. Frostick.)

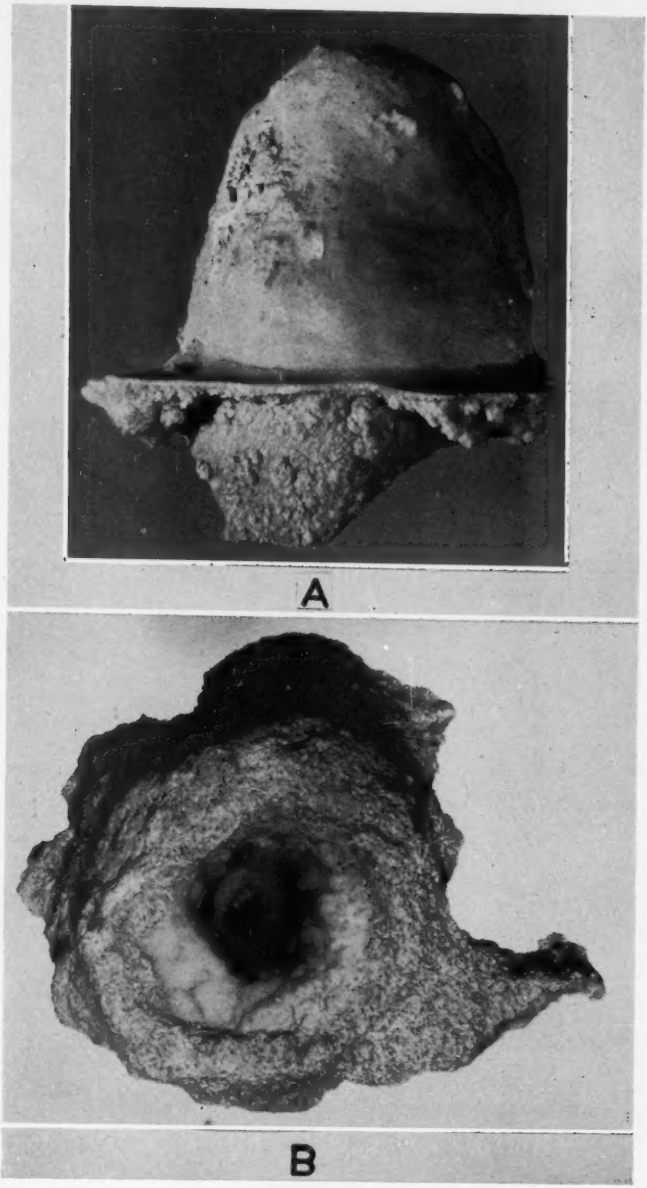

PLATE 3

the chamber, was 57° F. in all positions.

Analysis of cave water.—The cave water was analysed (table 2) by Mr. F. F. Field in the Victorian State Laboratories. It was collected from a feeder source yielding 214 drops per minute. The following results were obtained:

TABLE 2.—*Analysis of cave water from Pearce's Cave*

	Parts per 100,000
Chlorides (Cl)	94.3
Sulphates (SO_4)	8.7
Bicarbonates (HCO_3)	34.2
Carbonates (CO_3)	nil.
Calcium (Ca)	14.0
Magnesium (Mg)	4.3
Sodium (Na)	53.0
Hypothetical combination:	
Calcium bicarbonate ($Ca(HCO_3)_2$)	45.5
Calcium sulphate ($CaSO_4$)	9.5
Magnesium sulphate ($MgSO_4$)	2.5
Magnesium chloride ($MgCl_2$)	15.0
Sodium chloride (NaCl)	136.0
Total solids in solution	208.5

For comparison with the composition of cave water from Pearce's Cave, it may be noted that Melhuish and Deane (1937) recorded water in a cave at Apollo Bay as containing 138 parts of total chlorides per 100,000, and cliff waters (with a pH value of 8.5) at Cape Schanck in Victoria as containing over 200 parts per 100,000. The total chlorides are undoubtedly derived largely from cyclic salts. Whereas the cave waters from Angel Cave at Cape Schanck contain 36 to 39 parts of bicarbonate per 100,000 (Baker and Frostick, 1947), the concentration in Pearce's Cave in Loch Ard Gorge at Port Campbell is a little lower—34 parts per 100,000.

In Pearce's Cave, the equivalent quantity of $CaCO_3$ calculated from the bicarbonate present, amounts to 28.01 parts per 100,000. If the partial pressure of CO_2 within the cave is equal to its present atmospheric value of 0.00032, Johnston and Williamson's tables (1916) indicate that the solubility of the $CaCO_3$ at a temperature of 14° C. (=temperature of cave water = 57° F.) is 66 parts per 100,000. The concentration of $CaCO_3$ in the cave waters is a function of the equivalent amount of $CaCO_3$ present, divided by the solubility of $CaCO_3$ in parts per 100,000 at the known temperature of the cave waters. On a percentage basis, this results in a value of 42 per cent for the concentration of $CaCO_3$ in the waters of Pearce's Cave.

Relative humidity.—Since Pearce's Cave is a particularly wet cave, with water constantly dripping from the roof in many parts, it is assumed that the humidity is relatively high within the cave, especially as air circulation is low, and the floor of the cave is permanently wet in most parts.

Allison's symbol.—In connection with the growth of stalagmites in caves, Allison (1923) has shown that the factors which control the deposition of $CaCO_3$ may be limited to a consideration of five variables, namely the rate of drip, the amount of air circulation, the relative humidity, the temperature, and the concentration. A particular association of similar factors is also responsible for the development of pisoliths and ooliths in pools on cave floors (Baker and Frostick, 1947).

Accepting Allison's (1923, p. 123) determinations that;

(a) more than one drop per second is to be regarded as a fast-dripping feeder,
(b) over 2 cubic feet per second is a large air circulation,
(c) over 50 per cent is a fairly high relative humidity,
(d) over 68° F. is a high temperature, and
(e) over 50 per cent is a high concentration,

we can summarize the variable factors for Pearce's Cave as *DaHtc*, because the

rate of drip is high (214 drops/min.) in the pisolith-generating pools, the air circulation within the cave is low (0.15 ft./sec.), the humidity is high, the temperature is low (70° F., see below) and the concentration of $CaCO_3$ in the pool waters is also low (42 per cent). While concentration is in part controlled by the water temperature, and pool temperature is used in the calculation of the concentration of the cave waters, temperature considered as a variable factor concerns the evaporating conditions within the cave. Here "T," the temperature of the cave atmosphere, is 70° F. When this measurement was taken, however, the air temperature outside the cave was 73° F., about 6° F. above the January average, this month giving the peak temperatures for the year. It would thus seem best to leave the temperature symbol as "t", its general value, even though the actual measurement temporarily exceeded Allison's limiting value by 2 degrees.

The combination of factors symbolized by *DaHtc* is comparable with the ruling conditions in Angel Cave at Cape Schanck (Baker and Frostick, 1947), and similar to the variable factors requisite for the development of group 12 in Allison's (1923, p. 122) classification of stalagmites. The characteristics of this group of stalagmites are that (1) the splash cup is shallow, (2) the shape of the end face of the stalagmites is very blunt, (3) the rate of growth is 0.0008 cm/year and (4) the circumference is 139 meters.

In pools where only "spats" (pl. 2, B) are formed in Pearce's Cave, four of the variable factors remain the same as in pisolith-generating pools, but the rate of drip (10 drops/min.) is low, so that in summarized form the variable factors are *daHtc*, a grouping corresponding with group 28 in Allison's classification of stalagmites. In this group the splash cup is deep, the shape of the end face blunt, the rate of growth 0.0006 cm/year and the circumference 3.6 meters.

It has been shown that in both Pearce's Cave, Port Campbell, and Angel Cave, Cape Schanck, the general conditions can be summarized as *DaHtc*, but that in Pearce's Cave, low rates of drip occur where "spats" are formed. Slowly dripping auxiliary feeders also form small, smooth, bare patches on parts of the stalagmitic encrustation, these patches being surrounded by areas littered with lenticular pisoliths, and for such patches the variable factors can be symbolized as *daHtc*, i.e. the same as for "spat" formation. In Angel Cave, Cape Schanck, small regular pools beneath active feeders (with conditions DaHtc) are considered to be the splash cups of occult stalagmites. Hence rate of drip may have a bearing upon the alternative development of "pools" or "smooth patches," as well as persistence of the drip. That rate of drip may control such variation in part, is evidenced by the stalagmites in Pearce's Cave that grow upon the stalagmitic encrustation, only rare examples having splash cups. Here, rate of drip is the most likely variant responsible for (a) well-formed stalagmites growing upon the encrustation, and (b) the development of splash cups in some parts and of smooth bare patches in other parts of the stalagmitic encrustation.

Allison's work appears to be contradictory in regard to the potency of the rate of drip in modifying splash cups. Stalagmites growing under conditions *daHtc* are supposed to have deep splash cups, but on the other hand it has been shown (Baker and Frostick, 1947, p. 47) that slow-dripping feeders may account for the absence of splash cups in the few well-formed stalagmites found in Angel Cave at Cape Schanck. If Allison's assertion (1923, p. 116) is correct that the depth of a splash cup is increased by "AhT," "c" and "D", why should stalagmites growing under the conditions *DaHtc* have shallow splash cups, and those growing under the conditions *daHtc* have deep splash cups? In the first place, two factors "D" and "c" tend to produce deep splash cups, and in the second place, "c" alone has this tendency.

Carmichael's Cave

Marine erosion has played a greater part in the formation of Carmichael's Cave than in Pearce's Cave. Carmichael's Cave is more or less straight and parallel-sided, being 155 feet long, 25 to 30 feet wide, and 20 feet high. The width of the cave remains approximately the same along its entire length, so that there is no chamber as in Pearce's Cave. The floor rises gently to the rear of the cave.

The principal variant in Carmichael's Cave, as compared with Pearce's Cave, is in the nature of the cave floor. Owing to the closer proximity of Carmichael's Cave to the sea, and to the fact that marine incursions into the seaward end at least, are almost daily phenomena, the cave has a sandy floor from entrance to rear, and the cave atmosphere is generally at a rather lower temperature than in Pearce's Cave. The sandy floor is a constant feature, and is only interrupted by occasional exposed ledges and a few fallen blocks of Miocene limestone that protrude through the sandy floor (Baker, 1942). The sea sometimes penetrates to the rear of the cave, thus periodically upsetting the conditions requisite for pisolith and oolith formation. In April, 1947, for example, high seas apparently just reached the rear of the cave, and sand stalagmites (Baker, 1942) situated over half way along the cave and near its rear, that were still in their original positions of growth in December, 1946, had been undermined and tilted into abnormal positions. Moreover, areas of earlier-formed stalagmitic encrustations were exposed and the depressions thereon occupied by bicarbonate waters—a state of affairs non-extant in December, 1946. The pool waters on the stalagmitic encrustations at the extreme landward end of the cave now contained; (a) ferruginous clay (with gelatinous iron hydroxide) in some pools, (b) ferruginous pisoliths and ooliths in other pools, and (c) gray colored (calcareous) pisoliths and ooliths in yet other pools. In addition, occasional stalagmites with blunt upper surfaces had been exposed, and these possessed small cups 2 to 3 inches across and up to one-half an inch deep. In some of these cups, occasional small, angular, irregularly shaped pisoliths were cemented to the floors and lower parts of the walls of the cups.

The dripping waters issuing from the roof of Carmichael's Cave are not nearly as copious nor as numerous as those in Pearce's Cave. Consequently, stalactites, stalagmites, pisoliths and ooliths are fewer in number, although stalactites are still relatively common and of the same form and size as those in Pearce's Cave. The floor of Carmichael's Cave especially the central portion, besides being sandy, is well-trodden along its entire length by frequent visitors to the cave, a factor inhibiting the formation of secondary carbonate structures on these parts of the cave floor. Cementation of parts of the sandy floor near the walls, more particularly from half way along and thence toward the rear of the cave, has resulted in the formation of sand stalagmites, and also, right against the cave walls, stratified sand plasters. It is with such regions that the formation of pisoliths and ooliths is associated in Carmichael's Cave.

Air circulation.—The movement of the atmosphere in Carmichael's Cave is rather greater than in Pearce's Cave, owing to its more open character and closer proximity to the sea.

Air temperatures.—Air temperatures in Carmichael's Cave are generally lower than in Pearce's Cave. The temperatures, measured in the summer season of 1946 on the same day as those obtained in Pearce's Cave, are shown in table 3.

TABLE 3.—*Air temperatures in Carmichael's Cave*

Location	Temperature
Outside cave entrance	70° F.
At twenty feet in from the entrance	67° F.
In center of cave	65° F.
At rear of cave	63° F.

The fact that on the same day and at much the same hour, the temperature just outside the entrance to Pearce's Cave was 3° F. greater than just outside the entrance to Carmichael's Cave, is to be ascribed to the presence of a long stretch of sun-heated sand between Pearce's Cave and the sea, and also to the more sheltered position of Pearce's Cave. Carmichael's Cave, on the other hand, is much nearer the sea, and the sand just outside its entrance is kept wet by the sea most of the time.

Pool temperatures.—There were no bicarbonate water pools evident near the entrance to Carmichael's Cave, and very few between the entrance and up to half way along its length from the entrance. This is not surprising in view of tidal activity at the cave entrance. Pool temperatures toward and at the rear of the cave were identical with those in all positions in Pearce's Cave, namely 57° F. Locally, therefore, the temperature of the near-surface underground water shows no variation at a depth of 100 feet or so below the surface (the vadose waters in the caves being at least 100 feet below ground level).

Composition and relative humidity.—Presumably there is no great difference in the composition of the vadose waters in Pearce's Cave and Carmichael's Cave situated only one hundred yards or so from each other, consequently the pool waters in Carmichael's Cave were not analysed chemically. The possibility of a similar ground water supply in both of these caves is suggested by the equivalence of their pool temperatures.

The humidity of the cave would not be quite as great as that of Pearce's Cave, but since it is relatively wet most of the year, Carmichael's Cave is regarded as having a high humidity.

Concentration.—It is assumed that as the $CaCO_3$ concentration of the analysed water from Pearce's Cave was 8 per cent below the limiting value (=50 per cent according to Allison, 1923), the concentration of the supply in Carmichael's Cave would not vary sufficiently to alter the concentration symbol (c). The average rate of fall of drops of bicarbonate water from the roof of Carmichael's Cave was 1 to 2 drops per minute.

Allison's symbol.—In Carmichael's Cave, the four variable factors—concentration, temperature of pool water, relative humidity, and amount of air circulation—were generally similar to these factors in Pearce's Cave, but the rate of drip at the time of measurement was considerably less. In summarized form the factors for Carmichael's Cave are, therefore, *daHtc*, which is a combination of factors comparable with group 28 according to Allison's classification (1923), and the same as that for the auxiliary feeders that lead to "spat," etc. formation in Pearce's Cave. The deep splash cups predicted from such a combination of variables, are evidenced in Carmichael's Cave in the sand stalagmites (Baker, 1942), the small circumference of these probably being due to slow drip and the fact that the range of splash was limited by the very deep, constricted cups (pl. 3, B).

Calcareous deposits.—Most of the secondary calcareous formations in Carmichael's Cave are built up from the cementation of sand on the cave floor by slowly dripping bicarbonate waters and by seepage down the walls of the cave. The cave walls are plastered with ribbed stalactitic encrustations, often with complexly rippled and scale-like appearances. Of the numerous hollow stalactites dependent from the roof, many are completely dry in the summer season, although most of them act as feeder sources in wet periods. Compared to Pearce's Cave, however, water dripping from the roof is generally much slower and from fewer feeder sources, and, taken in conjunction with the sandy floor of the cave, it is, therefore, not surprising that bicarbonate water pools are an uncommon feature of Carmichael's Cave.

In depressions on the occasional calcareous crusts and in cups formed in the sand stalagmites, occasional loose cave pisoliths and ooliths occur, usually only

two or three at the most in the cups. One cup, however, contained nine pisoliths cemented on to its floor and walls. Many cups are devoid of pisoliths and ooliths; if they ever contained any, it is probable that the uncemented discrete bodies were washed away during a marine incursion. Most pisoliths in Carmichael's Cave come from the depressions on the calcareous crusts right at the rear of the cave. Terminal velocity of the waves during the 1946–1947 marine incursion was evidently competent to move sand and undermine some of the sand stalagmites, but incompetent to remove all of the pisoliths from the pool sites exhumed during the process. Otherwise the growth rate of some of these pisoliths must have been rather phenomenal. They provide no evidence of having increased in size or of having become cemented to sand grains during their period of burial under a cover of sand. The depressions on the calcareous crusts are supplied with bicarbonate waters largely by seepage down the cave walls. Two such depressions, fed by somewhat faster supplies of water, contained considerable quantities of ferruginous pisoliths. On the other hand, one depression, with 6 inches of water and 6 inches of reddish-brown slime and a little sand, was devoid of pisoliths and ooliths, but it possessed a prominent thin "roof" of calcium carbonate that has grown over the surface of the pool water for a distance of 9 inches from the edge of the pool.

Cave on London Bridge Beach

This cave was formed almost entirely by the undercutting effects of marine erosion at the base of cliffs 100 feet or so high. It is 70 feet wide, and has been undercut into the cliff for some 50 feet in depth and 35 feet in height. Although nearly 8 miles west of the two caves in Loch Ard Gorge, it has, nevertheless, been cut in similar Miocene limestones and calcareous clays, so that the source rocks for the supply of calcareous material are similar. Different conditions again obtain in this cave, which is much more open than either Pearce's Cave or Carmichael's Cave. The floor is principally sandy. Parts of the floor have been cemented, and irregular cascade-like stalagmitic encrustations with occasional poorly-formed stalagmites have been built up. These secondary structures are protected from marine erosion at the present day by a partially fixed, 12 foot high sand ridge, steeper on the cliff side and sloping more gradually on the seaward side.

Air circulation.—Air circulation is relatively free, and at times, strong air currents sweep along the walls and roof of the cave, diverting the pool feeders to a considerable extent. Due to the open nature of the cave, its atmosphere is rarely still, and even when not directly affected by the prevalent winds of the district, the air behind the sand ridge, protecting the entrance to some extent is kept moving by eddies competent to shift small sand grains. Indicative of a more powerful air circulation, diversion of the feeders has resulted in the production of several elongated pools with their long axes approximately parallel to the trend of the cliff line.

Air temperature.—The temperature of the cave atmosphere is more or less maintained at the temperature of the air against the cliff face, and in virtue of the free air circulation, can be expected to vary rapidly in close sympathy with the diurnal and seasonal fluctuations general throughout the district. Measured in the summer of 1946–1947, the temperature of the cave atmosphere was 70° F., and of much the same order of magnitude as the air temperature outside the cave.

For such open caves, Allison (1923, p. 123) has indicated that the average annual temperature and relative humidity for the district may be used in evaluating the evaporating conditions. From information contained in Australia Pilot (1944, pp. 30–31), it would appear that the average annual temperature of the Port Campbell district would be much below Allison's limit of 68° F. On more exposed parts of the South Coast, such as Cape Otway and Cape Northumber-

land, which lie on either side of the Port Campbell district, the January-February daily maxima average between 65° F. and 70° F. For the Victorian coastline generally, the hottest months are January and February, when the daily maxima average between 70° F. and 80° F. Nights are generally cool, with minima averaging between 50° F. to 60° F. In July, the coldest month, the day maxima average about 55° F., and the night minima 40° F. to 45° F. During extreme conditions, the temperature may occasionally fall below freezing point in winter, and rise above 100° F. during the hot north winds of summer. Over most of the year, however, the temperature would be low and the actual measurement of 70° F., obtained in the cave during the summer of 1946–1947, may be regarded as transient only.

Relative humidity.—As indicated in Australia Pilot (1944, p. 30), during the hot north winds of summer, the relative humidity may be under 30 per cent. Though no figures specifically relating to the Port Campbell district are available, it seems probable that over most of the year, the relative humidity would greatly exceed this value and also stand above Allison's (1923, p. 123) limiting value of 50 per cent.

From the charts given by Hunt (1914 figs. 1, p. 125 and 3, p. 129), it appears probable that the relative humidity of the Port Campbell district does not depart very widely from that of Melbourne. Both of these areas are approximately equi-distant from the 55° F. and 60° F. isotherms depicting the average yearly temperature, and show a reasonable agreement in their relationship to the mean wet bulb isotherms based on 9 A.M. observations—Melbourne having a slightly lower wet bulb temperature. From the tables for Melbourne, given in Australia Pilot (1944, p. 36), it is evident that only the 3 P.M. January average falls below 50 per cent—to the extent of 1 per cent—the 9 A.M. value for the same month being 58 per cent. The June values are the highest, giving 68 per cent for the 3 P.M. observation and 84 per cent for the 9 A.M. observation, while the yearly means are 56 per cent and 69 per cent respectively. It is obvious that only rarely throughout the year would the relative humidity of Melbourne descend below 50 per cent, and since it is probable that the relative humidity of the Port Campbell district would be, if anything, a little higher than that of Melbourne, it would likewise rarely be lower than 50 per cent.

Concentration.—It has been mentioned that the source rocks for $CaCO_3$ are similar to those of the two caves already described. The cave lies at much the same level as the two caves in Loch Ard Gorge, and is supplied by bicarbonate-bearing waters with a concentration not expected to vary sufficiently to bridge the 8 per cent gap between the proved concentration in Pearce's Cave and Allison's 50 per cent limit. Due to the open nature of the cave on London Bridge Beach, several analyses would be necessary to determine the actual pool water concentration, while variation in the numbers of green algae populating some of the pools would tend to render such analyses valueless. Due to the removal of CO_2 during photosynthesis (Twenhofel, 1939, pp. 332–336), these algae tend to alter the pool water concentration, virtually increasing it. On the other hand, temporary dilution of the pool waters may occur when rain water is delivered directly from the cliff face, and when salt spray is driven under storm conditions over the protecting sand ridge at the cave mouth. High winds may also result in deviation of the pool feeders, so that some of the bicarbonate-bearing solution falls beyond the pool margins to be absorbed by the loose sand constituting much of the cave floor. The fact that the sand of the cave floor is not cemented, however, supports the conclusion that the length of the elongated pools is largely determined by the amplitude of swing of the distal end of the feeders. Only under exceptional circumstances would the deviated drip completely escape falling into the pool.

In view of the uncertain duration of

the three factors tending to virtually lower the pool water concentration, and the unknown potency of the one factor tending virtually to increase it, the one alternative in arriving at an average estimate of the effective concentration appears to be in assuming that it is comparable to that of the two caves already described.

Feeder drips.—The feeder drips fall approximately 15 feet into pools situated about 20 feet from the cave entrance, and from lesser heights at the rear of the cave. The rate of drip above one pool full of green, algae-coated pisoliths, was 85 drops per minute. This pool was 30 inches long, 24 inches wide, and 1 to 2 inches deep, and the drips followed one another with regularity when observed in the 1946–1947 summer season. Two years later, however, the same feeder source had changed from supplying isolated drips to the pool, to a supply that left the feeding stalactite in "spurts" every few seconds. Conditions at the time of this later observation were such that the atmosphere was very still and humid, and there was no swing of the drips, which consequently fell into the center of the receiving pool below.

Allison's symbol.—It is obvious that the open nature of the cave on London Bridge Beach gives rise to variations in the evaporating conditions, while the presence of green algae and other factors are productive of variations in the pool water concentration. It is thus fairly certain that at times, variation must occur in the rate of pisolith growth, and in some pools it may occasionally cease altogether. The average conditions, however, would conform to Allison's symbol *DAHtc* over the greater part of the year. Under such conditions, stalagmites of class 4 may be expected to develop, these being characterized by shallow splash cups, very convex faces, rate of growth 0.75 cm/year, and a mature circumference of 4.4 meters. The fact that no stalagmites actually occur, or at best are only very poorly developed, may be ascribed in part to the loose, impermanent nature of much of the cave floor. Where fallen blocks of Miocene limestone intercept the feeders, the spacing of the feeders and the mature diameter of the postulated stalagmites is such that the $CaCO_3$ deposits coalesce to form stalagmitic encrustations.

Though a little different from those of the other Victorian pisolith-generating caves for which the growth factors are broadly known, the conditions within the cave on London Bridge Beach probably agree in all factors except air circulation, which is high, and the rather indeterminate effect of algal activity. Nevertheless, although the growth rate of stalagmites predicted for these conditions would be higher than that appertaining to the other Victorian caves so far dealt with, it is still far removed from that of the optimum conditions of stalagmite growth outlined in Allison's tables (1923, p. 122). Although it would appear that pisoliths formed in the cave on London Bridge Beach are developed under conditions with many possibilities of variation, the actual variations encountered are most likely of short duration, and pisolith growth generally proceeds under much the same circumstances as have been outlined elsewhere (Baker and Frostick, 1947, p. 47). While it is true that high air circulation in this cave gives better evaporating conditions, high humidity and low temperature still tend to keep the expected mature circumference of stalagmites within the range productive of stalagmitic encrustations rather than individual stalagmites.

Calcareous deposits.—In one of the pools in the cave on London Bridge Beach, there were over 100 pisoliths, mostly of rounded and elongated shapes. The pisoliths were all submerged and quite slimy when wet, because of the coating of algal growths. They rested in a depression in the sand, caused by the impact of falling drops of water. The surface of this depression had been rendered more or less impervious by the presence of residual clay from the dissolution of the source limestones, and by partial hardening of the surface by secondary cementation with calcium car-

bonate. A little loose sand and occasional blades of marram grass in the pool, which had been recently blown there, and similar materials have acted as nuclei for the precipitation of $CaCO_3$.

A dozen or so additional depressions on the floor of this cave mostly contained water, but not all contained pisoliths, and ooliths were completely absent from all the pools here. Some of the pools contained a sprinkling of loose sand, others contained much whitish colored slime consisting of gelatinous $CaCO_3$ with impurities. As there was no such slime in pisolith-containing pools, and no pisoliths in slime-bearing pools, it would appear that this state of affairs provides adequate testimony to the belief that the precipitation of $CaCO_3$ in pisolith growth, occurs in the crystalline rather than in the gelatinous state. About half a dozen pools with clear bicarbonate water contained pisoliths, while two dry depressions had numerous pisoliths, the longer forms of which are slender, (pl. 2 C), very brittle, and had been deposited around blades of marram grass or dried fragments of wind-blown seaweed. Some of these pisoliths are bean-shaped and some still contain fragments of blades of grass or of seaweed (pl. 2, D); others have a cylindrical, hollow center from which the blade of grass or seaweed fragment has been removed as a result of organic decomposition.

Occasional stalagmitic encrustations beneath the dripping stalactities, on large fallen blocks of limestone, contained a few pools. One of these pools, 6 inches long, half an inch to 2 inches wide and 2 inches deep, contained 15 pisoliths and a sprinkling of wind-blown sand. The floor of this pool was smooth and hard. Other pisoliths in nearby depressions had become cemented to the stalagmitic encrustation. Ferruginous pisoliths are lacking from the cave on London Bridge Beach. When the greenish-colored, slimy coating of organic matter (algae) is removed from the calcareous psioliths, they are of a much darker color than those of kindred composition found in Pearce's Cave and Carmichael's Cave.

CHARACTERISTICS OF THE PISOLITHS, OOLITHS AND ASSOCIATED CALCAREOUS GROWTHS

Pisoliths and Ooliths

Composition.—The discrete bodies known as pisoliths and ooliths, from the three caves in which they have been formed in the Port Campbell district, are chemically of two principal types: a) calcareous, and b) ferruginous.

Solubility tests, using $\frac{1}{2}$N HCl, indicate that the ferruginous varieties are largely calcareous with variable amounts of ferruginous salts that are completely soluble in hydrochloric acid. Color variations among the pisoliths and ooliths are entirely due to the varying quantities of iron salts present. Table 4 indicates the qualitative solubility of the several occurrences of pisoliths and ooliths.

TABLE 4.—*Qualitative solubility of some pisoliths and ooliths*

A. *Cave on London Bridge Beach*

Many pisoliths from this cave have soluble interiors but insoluble green, slimy exteriors. A few have completely soluble exteriors, but insoluble green interiors composed of fragments of marram grass blades.

B. *Carmichael's Cave*

1. Light brown varieties are completely soluble, a faint green solution being due to small amounts of iron salts.
2. Dark brown varieties are completely soluble, the solution being more strongly colored yellowish-green from rather greater concentrations of iron salts.

C. *Pearce's Cave*

1. Flesh-colored and grayish-colored pisoliths and ooliths of different shapes having various kinds of surfaces, are all completely soluble and give clear, colorless solutions.
2. Pale brown-colored varieties are completely soluble, a faint yellowish-green solution resulting.
3. Dark brown ferruginous varieties dissolve with fairly strong effervescence, a dark brownish-red solution resulting. As with all other varieties tested in acid, there was no insoluble residue of clay or any other solid matter.

All pisoliths composed entirely of calcareous matter take a fair polish, although occasional specimens are relatively porous and hence do not take a high polish. Examples from the cave on London Bridge Beach, where associated with green algae, are extremely porous and polish poorly with difficulty. Ferruginous pisoliths, certain of which are very brittle, do not polish as well as the porous, more solid calcareous pisoliths, and their surfaces tend to crack like breadcrusts. The internal structures of the pisoliths and ooliths are similar to others previously described (Baker and Frostick, 1947).

Density.—There is a considerable range in densities among the various kinds of pisoliths, as shown in table 5.

TABLE 5.—*Density of some pisoliths and ooliths*

Locality	Variety	Density
Cave on London Bridge Beach	Grayish	2.237
Carmichael's Cave	Dark brown	2.568
	Grayish	2.617
Pearce's Cave	Ferruginous	2.470
	White, bisque	2.602
	White, polished	2.611
	Light brown, encrusted	2.624
	Grayish, bisque	2.628
	Grayish, lens-shaped	2.634

The variation in density from type to type is a reflection of variation in porosity, as in the Cape Schanck (Victoria) pisoliths (Baker and Frostick, 1947). It is seen from table 5 that more highly porous varieties, viz. the grayish-colored pisoliths from the cave on London Bridge Beach, the dark brown pisoliths from Carmichael's Cave, and the ferruginous varieties from Pearce's Cave, have considerably lower densities than compacted calcareous pisoliths. Nevertheless, the density of all of the calcareous pisoliths is appreciably less than that of calcite ($d = 2.714$), indicating that even the compacted calcareous pisoliths are also somewhat porous. Slight variations in density between different types of the calcareous pisoliths are ascribed partly to differences in porosity, and partly to the presence of nuclei that vary in size and character. The temperature of formation of the Port Campbell pisoliths (57° F.) is generally similar to that of the Hammam Bou Hadjar (North Africa) pisoliths which consist of calcite, and were formed in spring waters at 63° F. (Royer, 1939). Aragonite apparently develops at higher temperatures, pisoliths composed of aragonite from Hammam Meskoutine in Algeria, being formed in spring waters having a temperature of 95° F. (Royer, 1939).

Mode of occurrence, shape and size.—In Pearce's Cave there occurs a multitude of pisoliths and ooliths both (a) included within pools, and (b) lying loose on the stalagmitic encrustation that covers parts of the cave floor. Those on the stalagmitic encrustation are principally lenticular in shape (pl. 1, E) and usually small in size, averaging 8 mm across; rounded varieties are seldom over 10 mm across. Rather than having been washed or splashed out of crowded pools, where lenticular pisoliths are seldom found, it would appear that these pisoliths actually formed more or less in place on the stalagmitic encrustation, in waters seeping over and splashing from the cave floor. The rate of seepage of such waters varies seasonally, e.g. with the influx of vadose waters from the cave roof in wetter periods. Wherever the cave floor is very wet, or even only damp, the lenticular pisoliths are free. Only parts of the floor now dry possess lenticular pisoliths cemented to the stalagmitic encrustation or to the floors of shallow depressions that represent the sites of dried-up pools.

The pisoliths in Pearce's Cave vary in color. Most are white to grayish, but some are brown and reddish-brown. The white and grayish varieties are composed of calcium carbonate; the reddish-brown and brown varieties (pl. 2, E) are ferruginous and are composed

of calcium and iron carbonates. Reddish-brown varieties are formed in pools containing discolored waters and usually some slime, the slime consisting largely of hydrous iron oxide in the gel state. One lenticular pisolith lying on the stalagmitic encrustation in the path of an iron-rich, slimy trickle, has its under surface stained brown, and the upper, smoother surface has remained grayish colored.

The larger pisoliths in Pearce's Cave range up to three-quarters of an inch in length. They are uncommon, however, and only occur in a few pools where they are always to be found on top of a crowded assemblage of smaller pisoliths underlain by ooliths. Some of these larger pisoliths immersed partially in pool water, continue to grow at water level and above water level more extensively and more rapidly than submerged portions of the same pisolith, obviously as a result of splash more than anything else. Hence such larger pisoliths grow asymmetrically, and their bases are sometimes bevelled due to the shape of the pool floor with which they are in contact, but to which they have not yet become cemented. Some of the larger pisoliths that rest upon a piled mass of smaller forms in the crowded pools of Angel Cave at Cape Schanck, Victoria (Baker and Frostick, 1947, p. 49), likewise had upper surfaces projecting above the pool surface. Growth was concentric due to the fact that the projecting pisoliths directly intercepted the feeder drip. On rare occasions, a small pool may have only one pisolith and of such a size that it almost infills the pool completely. The pisolith remains free and can be lifted out, but its size and shape is determined by the size and shape of the pool. Such examples provide excellent evidence that static pisoliths do not necessarily become cemented in place. They could be regarded as small units of the stalagmitic encrustation, growing separately from it, and at a different rate, because of better local supply and greater concentration of bicarbonate waters.

The pisoliths as a whole, including white to grayish, and brown and reddish-brown varieties, do not show the variety of shapes like those from Angel Cave at Cape Schanck, Victoria (Baker and Frostick, 1947). The pisoliths here being studied are principally irregular (pl. 2, A and E) to rounded (pl. 1, A) or lenticular (pl. 1, E) in shape. One small pool, 1½ inches across, in Pearce's Cave contained larger irregularly-shaped pisoliths on the top, and the shapes of the smaller pisoliths underneath had been determined by contact with the larger overlying pisoliths (pl. 1, C). Egg-shaped, well-polished ooliths occurred at the bottom of this pool, indicating that the supplying feeder was relatively fast-flowing, resulting in sufficient turbulence in the lower water layers of the pool to cause buffing and polishing by agitation, but the larger pisoliths were unaffected by this process.

Pisoliths and ooliths with rough, papillate surfaces (pl. 1, D) occurred only in pools fed by slowly moving surface seepage waters and thus almost stagnant. The greatest number of pisoliths and ooliths occurred on the flatter areas of the stalagmitic encrustations, on the cave floor below the slopes of stalagmitic cascade-like structures.

In one depression that had almost dried out, and was only damp in patches, seven well-rounded pisoliths had become attached to one another by the merest film of $CaCO_3$ at their points of contact. Four similar pisoliths beneath them were too firmly cemented to the floor of the depression, and to one another, to be removed without fracturing. Each of the slightly attached pisoliths shows small facets at the points of contact, and equatorial fracture lines from which one or two smaller cracks lead off approximately at right angles (pl. 1, A). These cracks are evidently due to stresses created by crystallisation of the carbonate films uniting the pisoliths at the facets.

Ooliths are extremely numerous in some pools and on parts of the stalagmitic encrustation. They range in size

from 2 mm down to one-fourth mm across, are usually rounded to ellipsoidal in shape, and are composed principally of white to grayish-colored calcium carbonate, although a few are brown from small amounts of iron carbonate.

In Carmichael's Cave, pisoliths from the cups in the sand stalagmites (pl. 3 B) are few in number (two to three at the most in any one cup). They are irregular in shape, with prominent edges somewhat rounded, and are found only in one or two of the cups. A few examples are compound and consist of several smaller pisoliths and ooliths united by cementation under stagnant conditions. Comparable multiple forms of pisoliths and ooliths are more commonly found among the dark brown varieties in Carmichael's Cave.

The darker gray pisoliths sometimes possess incomplete girdles (pl. 1, B) represented by slightly elevated, narrow ridges of $CaCO_3$. Such structures are in a way comparable with the "plimsolline" effect noted in Angel Cave, Cape Schanck (Baker and Frostick, 1947).

In the cave on London Bridge Beach, nearly all the pisoliths (pl. 2, A, C and D) possess bisque surfaces. Some examples have become rather smoothed by oscillation in the pool waters, but are never well-polished all over. Rare examples provide evidence of a little buffing on the more exposed portions, due to more vigorous agitation.

Other Calcareous Growths

"*Spats.*"—"Spats" occur in Pearce's Cave on top of the reddish slime occurring on the floor of a pool measuring 56 inches by 33 inches and containing $1\frac{1}{2}$ inches of water and $1\frac{1}{2}$ inches of mud. The only $CaCO_3$ deposited in this pool was in the form of thin plates (pl. 2, B) encrusting the mud immediately beneath feeders dripping at the rate of one drop in 10 minutes.

One specimen (pl. 2, B) shows a radial arrangement of rather interrupted, irregular raised ridges on the concave upper surface, and a pair of off-center perforations. Near the center of the convex lower surface is a mass of haphazardly arranged platy fragments that appear to be earlier-formed plates displaced by a temporarily more powerful feeder.

The pool containing the "spats" is fed more by seepage across the cave floor than by the slowly-dripping overhead feeders. Hence it seems probable that the "spats" were formed beneath a water cover rather than in the mud of the pool. As the "spats" are formed in this way, it may be concluded that the momentum of the falling drop from the slowly dripping overhead feeders, supplies energy for the production of eddies capable of scouring shallow basins in the muddy floor of the pool. Furthermore, since $CaCO_3$ deposition is dependent upon the escape of CO_2 from the depositing solution, as well as normal aqueous evapotion, and the rate of escape of CO_2 is accelerated by agitation, deposition on the pool floor tends to become localised beneath the eddy zones produced by the overhead feeders.

Because they are localised beneath overhead feeders, "spats" may be regarded as sub-aqueous stalagmites. The curve of the upper surface is not, however, comparable with the splash cups of normal stalagmites, the degree of concavity being influenced by the depth of water in the pool and the energy of the feeder. The curve of a "spat" would not approach the form of a splash cup until its rim emerged above the pool surface, when the pool itself would only receive splash and overflow from a cup able to retain a richer depositing solution agitated by a higher percentage of the force supplied by the feeder drip. Then the rate of vertical growth of the rim would be accelerated and the original embryo stalagmite or "spat" would tend to assume a form characteristic of the conditions promoting normal stalagmite growth. The occurrence of "flanged islets" (pl. 3, A) may indicate that stalagmites can grow in this way from the floor of a pool. One pool in Pearce's Cave had specialized in the formation of "flanged

islets," some six or seven occurring in the one pool from which pisoliths were absent. The bicarbonate feeder sources in this pool were relatively slow drip combined with gradual surface seepage.

Splash cups of sand stalagmites.—The splash cups of the sand stalagmites in Carmichael's Cave are abnormally deep (pl. 3, B), though it is true that Allison (1923) predicts deep splash cups for stalagmites growing under the conditions *daHtc*. The deepest splash cups, however, may be expected in stalagmites of class 6, developed under conditions *DAhTc*, because (see Allison, 1923, p. 116) the depth of splash cups is increased by high evaporation "AhT," low concentration "c," and rapid drip "D." The diameter of the cup, on the other hand, is affected by the height of the drip, i.e., the greater the distance of fall, the greater the diameter of the "splash cup."

The mature circumference of stalagmites growing under conditions *daHtc* is approximately 3½ meters, a dimension never attained by other than compound sand stalagmites. The small circumference of these forms is due to the slow growth rate of 0.0006 cm/year, and their immaturity. Development is stinted initially by limitation of the range of splash by the loose sand floor upon which they grew, by forced vertical growth due to deposition of additional sand layers on the floor. The consequent development of deep splash cups limits the range of splash from the feeders.

It seems likely that the deep splash cups of most sand stalagmites are due to the fact that they were initially drilled in the loose sand of the cave floor by the feeders, and their form rendered more permanent by cementation of their sand walls (Baker, 1942, p. 666). A further increase in depth of the cups occurred during deposition of additional sand layers, drilled in coincidence with the first-formed cup, which would also be cleared of sand. The probability of this method of forced vertical growth being true is indicated by compound sand stalagmites (Baker, 1942, figure 3) possessing short adventitious splash cups which, through cessation of the feeding drip, have ceased vertical growth at levels inferior to those attained by more persistent drips. In course of time, below positions of closely spaced drips, compound stalagmites unite to build up a stalagmitic encrustation several feet across. Sand stalagmites may, therefore, ultimately become stalagmitic encrustation in gradual stages, marked phases of which are (1) drilling of holes of small diameter and about 1 inch deep in the loose sand of the cave floor, (2) transition of these holes into permanent splash cups by carbonate cementation of the retaining walls of the drip-holes, (3) lateral spread of cemented areas with partial infilling of splash cups by layers of carbonate encrustation and cementation of contained pisoliths, (4) complete infilling of the splash cups with secondary carbonate and upward continuation of growth to form short, blunt stalagmites, (5) union of neighboring single sand stalagmites by lateral spread of cementation to form sand stalagmites of compound character, (6) lateral spread of sand stalagmite encrustation by further growth of single sand stalagmites around the periphery of the encrustation and increased lateral cementation by bicarbonate-bearing waters seeping across the encrustation.

It is of especial interest to note that under the conditions *daHtc*, "spats" have been formed in Pearce's Cave, and "sand stalagmites" in Carmichael's Cave. The "spats" may be considered as subaqueous stalagmites in an incipient stage of growth, and the "sand stalagmites" as immature forms of forced vertical growth. In the first place, the energy of the feeders produces subsurface eddies in a pool, and in the second place it displaces loose sand during the initial growth and perpetuation of the splash cups in the sand stalagmites. Both of these examples may be regarded as in part due to impact phenomena, produced at an incipient stage of abnormal stalagmite growth.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 21, NO. 2, PP. 105–108
FIG. 1, JUNE, 1951

TRENDS IN LITERATURE OF SEDIMENTOLOGY[1]

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ABSTRACT

The annual number of articles published in sedimentology and other fields of geology is increasing at a rapid rate. Progressively greater specialization of journals and the preparation of bibliographic aids have helped to cope with the influx of articles during the past. However, unless a "Geological Abstracts" soon becomes available, research workers are likely to become either narrowly specialized or superficial in their searches of the literature.

One commonly hears the statement amongst geologists that much more is being printed than one can possibly read. Out of curiosity the writer decided to compile some statistics on the publication of articles in geology and especially in sedimentology. The source was the series of U. S. Geological Survey Bulletins Nos. 746, 823, 937, 938, 949, 952, 958, and 968, entitled "Bibliography of North American Geology." These include most geological articles concerning North America that were published between the years 1785 and 1948, inclusive. The number of articles for each year during this period was counted and plotted on figure 1. Number of pages published annually probably would have given similar results because the average length of 200 randomly selected articles published prior to 1900 was 28 pages, as compared to 27 pages for 200 articles that appeared in 1948. Wentworth and Apfel (1927) also found an average length of 27 pages for 2200 articles published in 1921 and 1922.

The upper graph on figure 1 shows a rapidly increasing number of articles from fewer than 50 per year before 1833, to more than 2400 in 1948. In spite of irregularities, extrapolation of the general curve suggests that an annual output of 5000 articles by 1975 is not unreasonable. The rapid increase during the past few decades closely parallels the growth of membership in the four largest American geological societies, according to statistics on societies compiled by a committee headed by Heroy (1950). Reasonably enough, the curve of annual oil production in the United States is also similar in shape. The dip of the graph of publications between 1941 and 1948 accents the loss of more than 5000 published articles during World War II. A broader, but shallower dip occurs during the years of World War I. These dips and especially their effect on off-setting the general curve to the right, question, at least for the field of geology, the contention by some that war promotes research. A similar drop during World War II is also exhibited in the number of college students majoring in geology (Heroy, *et al.*, 1950) and in the annual expenditures of the Geological Society of America (Aldrich, 1950). An average of 4100 articles per year from foreign (non-North American) sources are listed in the Geological Society of America's "Bibliography and Index of Geology Exclusive of North America" from 1933 to 1949, inclusive. These range from a high of 5386 in the volume for 1939 to a low of about 1000 in 1943. The foreign output was not included in the graph because listings since about 1942 are somewhat incomplete, owing to delays in delivery and to limitations in the size of the bibliographic staff (Marie Siegrist and Marjorie Hooker, personal communications). Altogether, however, it is evident that

[1] Contribution of Allan Hancock Foundation, University of Southern California, No. 70.

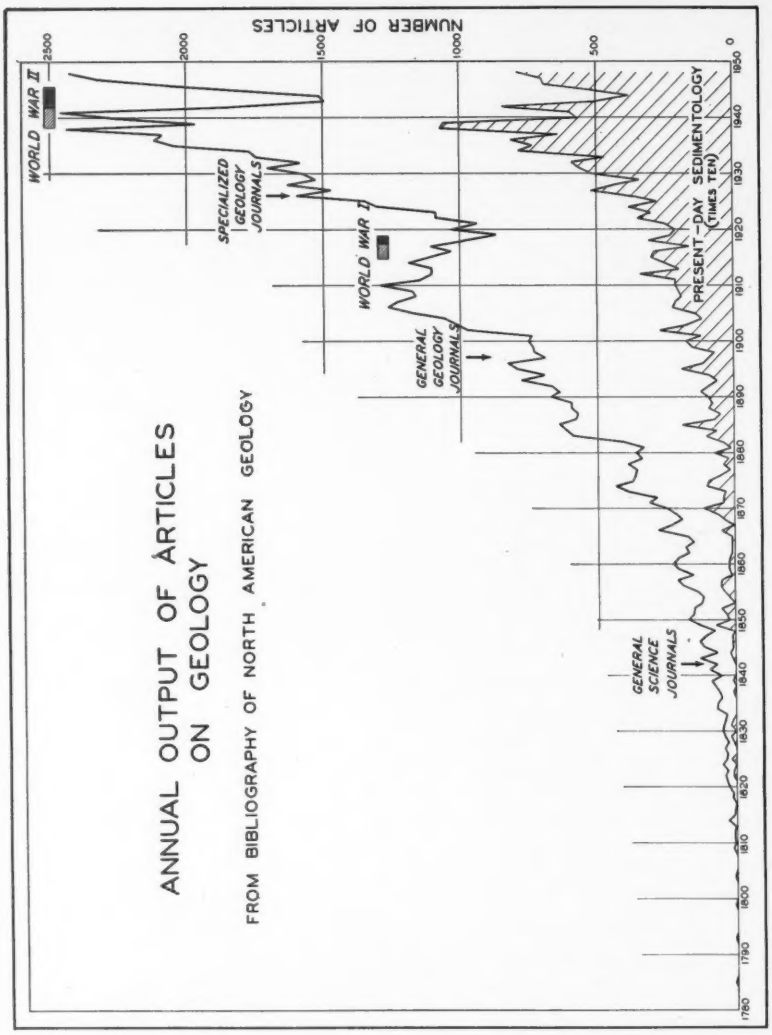

FIG. 1

more than 6000 geological articles per year are now published. Even if all were accessible and in easily translated languages, one would have to read more than 500 pages per day to keep up with all of the literature, disregarding the back-log of probably more than six million pages.

What is the situation for the particular restricted field of sedimentology? In the broadest sense, sedimentology includes sedimentary processes, description of present-day sediments, methods of study,

and interpretation of sedimentary rocks. Because the latter section overlaps stratigraphy and is commonly difficult to identify from titles alone, it was not included in the study. Articles belonging to the other sections, with accent on present-day sedimentology, were counted and plotted as the lower graph of figure 1. These comprise less than half the total for general sedimentology and only about 2½ per cent of the total output in geology. About 100 American articles on present-day sedimentology per year are now being published, and, although the foreign output was not counted, a reasonable estimate of the total (American plus foreign) is 250 per year. If fifty be taken as the number of articles that the average sedimentologist reads indiscriminately each year just to keep informed, then the total output is about five times the number that are read. With such incomplete coverage, research workers tend to follow one of two alternatives. Probably the first of these is a tendency to read only the articles that appear to be of greatest immediate interest in the journals to which one subscribes and those in reprints that one receives. Little effort is spent on securing and reading foreign-language articles. As a result, there is a strong tendency for research to be carried on in the United States that closely parallels current or past research in Europe. The converse is probably also true. Such a duplication has the minor virtue of checking interpretations, but it has the great objection that it defeats one of the purposes of research: to form foundations on which later research can be built. The second alternative is to develop a higher degree of specialization in one's reading. By selecting a sufficiently small section of sedimentology, it may be possible to read most of the output. To show how this limits the field, the writer arbitrarily grouped all North American articles on present-day sedimentology into nine main groups (table 1). Chief of these is the marine field, mostly beach studies, to which about 30 per cent of the articles belong. The main objection to great specialization, of course, is that the worker may not become aware of developments in related fields that are applicable to his problems. A narrowed viewpoint also prevents him from visualizing the relationship of his results to the larger problems of geology.

TABLE 1.—*Distribution of sedimentology articles*

	1785–1931	1932–1948
Total Number	1198	1173
	per cent	*per cent*
Marine	28.2	32.5
Lakes	14.0	19.6
Streams	17.0	14.4
Miscellaneous, mostly methods	9.3	10.9
Wind	8.7	6.9
Weathering and soils	5.7	5.6
Ground water	6.9	4.9
Gravity	6.8	4.0
Glacial and frost	3.4	1.2
	100.0	100.0

Until about a hundred years ago it was possible for a man to become well enough acquainted with several fields of science to be able to make contributions to all of them. This "well-rounded education" characterized such men as Fridtjof Nansen, Charles Darwin, and others particularly of the explorer type. The number of scientific papers that were published was not so great but that any one man could, if he wished, read a large percentage of the literature in each of several fields. He, then, was perhaps a sort of general practitioner. A highly varied assortment of articles are to be found in the journals of that day. such as *Comptes Rendus of the Academy of Science in Paris, Proceedings of the American Philosophical Society, Science,* and *American Journal of Science.* Many of these general publications are still active and still include the same wide range of subject matter. In time, the volume of articles so increased that new journals were established to carry only articles in single fields of science, such as geology, physics, chemistry, or zoology.

Examples of these are the *Journal of Geology*, the *Bulletin of the Geological Society of America*, and the *Geological Magazine*. The number of articles in each field, however, soon became so great that bibliographic and abstracting services were required to make known and to locate references on particular subjects. Among these are the *Bibliography of North American Geology*, *Chemical Abstracts*, and *Biological Abstracts*. Still later, the increased volume of research required even more specialized journals to serve as outlets for publication, as sources for retrospective searches, and as concise collections of reports on current research. At this time such publications as the *Journal of Sedimentary Petrology*, *Journal of Marine Research*, and *World Petroleum* came into being. The dates of founding of examples of these different classes of journals were summarized and averaged to find how closely they correspond to the increase in number of published articles. Ten American general science journals that contain some articles on geology began between 1769 and 1893. Their average date of beginning is 1842. Seven American journals that contain only articles on geology, but on all fields of geology, began between 1880 and 1917, averaging 1897. Six American bibliographic or abstracting services for different sciences began between 1886 and 1937, averaging 1915. Finally, 21 American journals that specialize in only single sections of geology began between 1895 and 1949, averaging 1925. A more exhaustive analysis would result in average dates not materially different from these. A similar, but earlier, development of journals occurred in Europe, as well described by Verdoorn (1948) with accent on the field of botany.

Now that the problem has been outlined, one might ask what can be done to solve it. The best solution might be the preparation of a *Geological Abstracts* similar to *Chemical Abstracts* which many chemists peruse regularly in order to keep informed. This was, in fact, suggested about 30 years ago by Tilley (1919). With adequate abstracts only those articles of especial interest or those needed to solve particular problems need be read in their entirety. However, such an abstracting service is expensive and not to be undertaken lightly. Even the well-established *Chemical Abstracts* is having financial difficulties that have led to a reduction in number of entries in indexing and, thus, to a reduction of its usefulness in research (Emery, Crane, and Taylor, 1950). Until such a service is available to geology, some relief can certainly be obtained by more careful preparation of abstracts and conclusions for articles, for, if the main results be outlined there, many readers will be able to obtain all the information that they require without reading entire articles.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 21, NO. 2, PP. 109–120
PLATE 1, FIGS. 1–8, JUNE, 1951

BEACH SANDS OF THE MEDITERRANEAN COAST OF EGYPT

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ABSTRACT

Data on the mechanical analysis and the mineral content of beach sands from the Egyptian Mediterranean Coast are presented. The sands are of two principal types, carbonate sands and quartz-dominant sands. On the west, from Dichkeila to Mersa Matruh, they are mainly composed of pure carbonate "oolites" with few shell fragments and almost no heavy minerals. These "oolites" are believed to be derived from the Western Desert Tertiary limestone formations, as wind-borne carbonate sands which have been reworked by the agitating water movement of the beach waves, acquiring further well-rounded character. Shape is not exactly spherical, but is rather irregular with a tendency to be ellipsoidal or elongated rods. "Oolites" away from the sea water are usually fairly indurated and under the microscope show cementation by a fine-grained mosaic of secondary carbonate (probably calcite). Because of their different character and origin from the common oolites, it is proposed to call these carbonate sands "pseudo-oolites."

From Dichkeila to Rosetta, the beach sands consist essentially of quartz grains with common shell fragments and an abundance of heavy minerals. These sands are believed to represent water-borne sediments transported mechanically by the Nile River, derived mainly from the Abyssinian Plateau, and subsequently mixed with shell fragments on the beach.

INTRODUCTION

The Mediterranean Coast of Egypt (fig. 1 A) extends from Sallum on the western boundary to Rafh on the eastern boundary, between longitudes 25°12′ E. and 34°10′ E. and in most parts above the latitude 31° N. This coast, which reaches about 900 kilometers in length, is cut by two branches of the Nile river, one at Rosetta and the other at Damietta, enclosing a wide alluvial delta in between. Near its eastern side the coast is characterized by the junction of the Mediterranean Sea with the Red Sea through the Suez canal, running from Port-Saïd on the Mediterranean to Suez on the Gulf of Suez.

The Mediterranean Coast dates mainly from the Pleistocene to the Recent. The present paper is a preliminary study of the mechanical analyses and mineralogy of a number of samples collected from the Mediterranean beach sands between Rosetta and Mersa Matruh. No previous sedimentologic study of this part of the beach has been published as far as the author is aware. Ball (1939) mentioned the "oolitic" limestones of the Mediterranean Coast west of Alexandria. He has given a brief geologic description of the field occurrence of this type of rock as one of the deposits of the Pleistocene and Recent of Egypt.

The Mediterranean Coast of Egypt can be arbitrarily divided into three parts, based mainly on the general differences in topography and lithology. These parts are:

1) The Western part, west of Rosetta,
2) The Middle part, between Rosetta and Damietta, and
3) The Eastern part, east of Damietta.

This paper is mainly concerned with the Western part.

TOPOGRAPHY AND LITHOLOGY OF THE WESTERN PART OF THE EGYPTIAN MEDITERRANEAN COAST

The geology of this part can best be discussed under two principal subdivisions based on differences in lithology, particularly of the carbonate content. These subdivisions are: 1) The Western part from Alexandria (specifically from

[1] On an Egyptian Government fellowship from the Dept. of Geology, Farouk 1 Univ., Alexandria, Egypt.

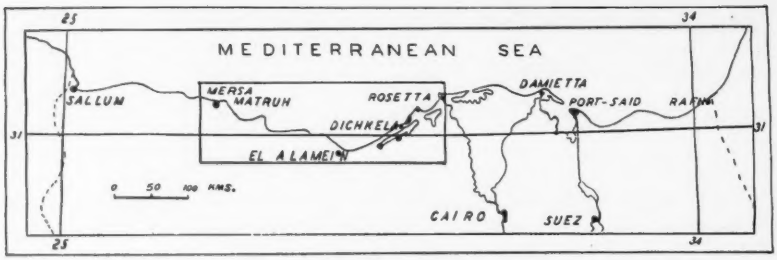

FIG. 1a.—Map of the Mediterranean coast of Egypt.

Dichkeila) to Mersa Matruh, very rich in the carbonate content and "oolitic" in texture; and 2) The Eastern part of Alexandria to Rosetta, poor in its carbonate content as compared to the Western part.

1) The Western Part of Alexandria: this part specifically extends from Dichkeila to Mersa Matruh. The beach sands are composed of loose carbonate sands, "oolitic" in texture, white in color, well-polished and well-rounded. Away from the sea water the loose carbonate oolitic sands gradually change to a fairly consolidated oolitic limestone forming ridges skirting the coast. A first ridge averaging 10 to 20 meters in height is found near the beach, and extends parallel to the shore for long distances (figs. 2 and 3). A second limestone ridge runs parallel to the first at a distance of a few kilometers inland, and there is in some places a third ridge between the second one and the edge of the Libyan Plateau. In some places the area between the shore ridge and the one next inland from it, is occupied by salt lagoons and marshes, in others, by a mixture of clay and lime material. A second strip of this material usually separates the second ridge from the third one or from the Libyan Plateau farther south. At the foot of the escarpment which forms the commencement of the Libyan Plateau, the thinned out edges of the "oolitic" limestone deposits can, in some places, be seen to rest upon the Miocene limestone of which the plateau itself is composed. Samples from drilled wells in the lime-clay material between the successive ridges prove that the "oolitic" deposits underlie this surface material and extend there to a depth below the sea level (Ball, 1939). In a deep boring drilled some years ago

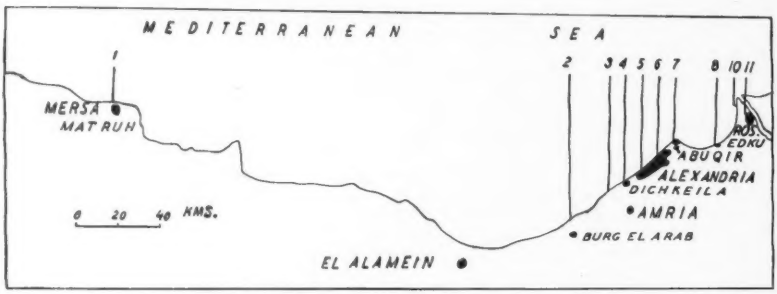

FIG. 1b.—Location of samples.

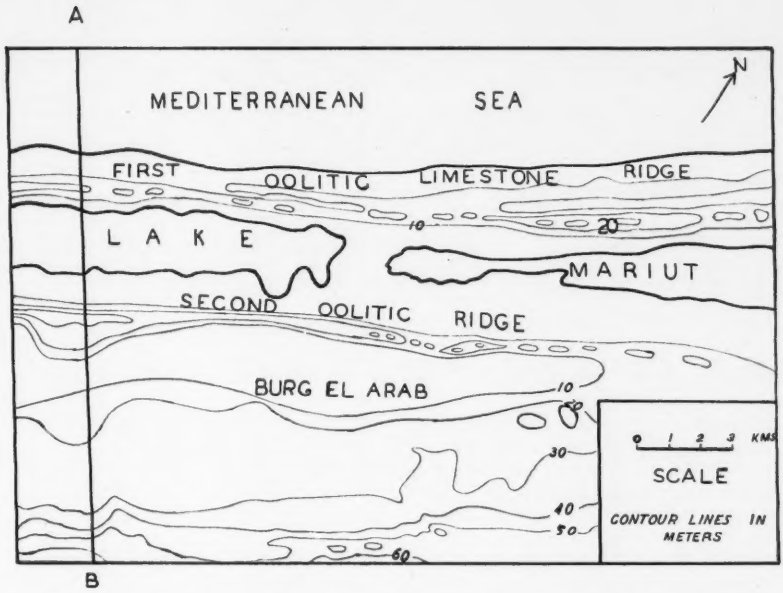

FIG. 2.—Topographic map showing the main field occurrence of the oolitic limestone along the Mediterranean coast (Burg el Arab area).

in a vain search for oil at a point in the Western Desert, three kilometers to the southeast of Mersa Matruh, the base of the "oolitic" limestone was found to be about 43 meters below sea level. The "oolitic" sand and limestone are characterized in the field by: 1) absence of true bedding, 2) absence of macro fossils with the exception of some scattered shells of recent Gastropoda and Lamelli-

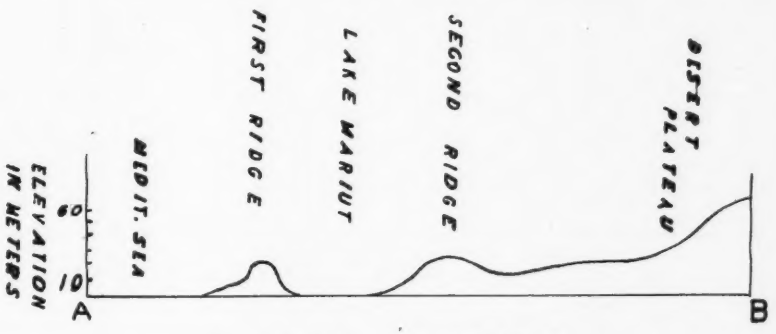

FIG. 3.—Profile section along A-B of Fig. 2.

TABLE 1.—*Statistical constants of beach sands from Egypt*

No.	Locality	Q_3	Md	Q_1	P_{90}	P_{10}	So	Sk	K	$CaCO_3$ percentage
1	Mersa Matruh	0.30	0.26	0.21	0.37	0.17	1.20	1.43	0.225	99.4
2	Burg el Arab	0.71	0.63	0.47	0.90	0.37	1.23	0.84	0.225	99.6
3	Amria	0.56	0.46	0.37	0.77	0.30	1.23	0.98	0.201	99.6
4	Dichkeila	0.29	0.25	0.19	0.40	0.14	1.21	0.89	0.192	99.0
5	Alexandria, Shatbi	0.35	0.27	0.26	0.55	0.22	1.16	1.25	0.137	90.0
6	Alexandria Sidi Bishr	0.60	0.35	0.25	1.3	0.21	1.56	1.22	0.316	69.4
7	Edku	0.29	0.25	0.24	0.39	0.18	1.10	1.12	0.118	36.4
11	Rosetta[1]	0.18	0.15	0.14	0.22	0.11	1.14	1.12	0.182	1.709

[1] Sample collected from a sand dune close to the beach for comparison.

branchia, 3) a highly polished surface of the grains, and 4) more or less uniform size of the grains. Microscopically, thin sections of the carbonate sands show: 1) a well-rounded character of the grains which range from one-half to one millimeter in diameter, 2) shape is rather irregular and tends to be ellipsoidal or rod-like, 3) a dominant mass of cryptocrystalline calcium carbonate forming the material of the grains, a concentric structure is uncommon, 4) a cementing mosaic of fine-grained secondary calcium carbonate (probably calcite) around some grains, 5) there are no nuclei in the real sense, and when occasionally a fragment of quartz is seen inside the carbonate grain, it does not occur in the center but somewhere near its margin, and 6) micro fossils of Tertiary and Recent Gastropoda, Lamellibranchia, and Foraminifera, of nearly the same size as the rest of the carbonate grains, with highly polished surfaces also.

After dissolving the carbonate sands with dilute HCl, a residue, of fine-grained quartz amounting to about 0.5 per cent by weight becomes noticeable. This fine-grained quartz probably represents dust impurities carried by the wind, the impurities becoming mixed with the carbonate sands. The origin of the carbonate beach sands will be discussed later.

2) The Eastern Part from Alexandria to Rosetta: This part shows a variation in the degree of consolidation of the sands which form its beach. The sands vary from loose to fairly well indurated deposits of quartz. Shells and shell fragments of Recent Gastropoda and Lamellibranchia are common in the beach sands of this part of the coast between Alexandria and Rosetta. From Abu Qir to the mouth of the Nile near Rosetta the beach sands show a relative darkness in color due to the relative enrichment of the heavy minerals. At the site of the black sands of Rosetta the shore is rather smooth and has no embayments; the sea currents are strong and tidal action is noticeable. This tidal action helps in collecting the heavy minerals concentrated there when the water level is low (A. M. Khalil[1]).

SAMPLING AND MECHANICAL ANALYSIS OF THE BEACH SANDS

Eleven samples were collected from the foreshore which, as defined by Trask (1939), is the zone lying between the ordinary high- and low-water marks. The samples were taken from different places to represent, as far as possible, the various kinds of beach sands (fig. 1 B). A 10 inch cylindrical tube was used for sampling by forcing it down into the sands. In the laboratory the samples were subjected to dry sieving for 20 minutes, through a set of screens of meshes No. 10

[1] Personal Communication.

16, 36, 60, 120, and 200, with openings of 2.001, 1.187, 0.437, 0.262, 0.131, and 0.081 mms in diameter as calibrated microscopically. After sieving, the separated fractions were weighed and the weights were expressed in percentage of the total sample. The data obtained were then represented as cumulative curves on semi-logarithmic paper (figs. 4 and 5). The third quartile, Q_3; median diameter, Md; first quartile, Q_1; the coefficient of sorting, So; the coefficient of skewness, Sk; and kurtosis, K, were calculated from the cumulative curves and are given in table 1. The weight percentages corresponding to the Wentworth scale (Krumbein and Pettijohn, 1938), were also calculated and represented in histograms (fig. 6).

About 10 grams of each sample were treated with dilute hydrochloric acid (1:3) to remove the acid soluble material (mainly carbonates), were filtered, washed, dried at about 110° C., and reweighed. The percentage of carbonate in each sample was thus determined by the difference (table 1). Qualitative tests made on the filtrates from all the samples indicate nothing in the way of bases but calcium. Only one or two samples show minor traces of magnesium.

TEXTURAL PROPERTIES OF THE BEACH SANDS

From the study of the cumulative curves (figs. 5 and 6) and the statistical data given in table 1, it is found that the beach sands of this part of the Mediterranean Coast of Egypt are, in general, composed of medium grains ranging in their median diameter from 0.25 to 0.63 mm. The beach sands are well-sorted (sorting coefficient, So, ranging between 1.10 and 1.56) and have a fairly symmetrical size distribution about the median. Whole shells as well as freshly broken shell fragments, wherever dominant in the sands, make the sediment poorly sorted.

The sand grains are well-rounded. This applies to both the carbonate and the quartz sands. Roundness in the carbonate grains is to be attributed to the continuous agitation by wind and coastal sea waters. The rounding of the quartz grains is probably due to its transportation by the Nile River from distant sources and by subsequent attrition by the coastal waters.

The calcium carbonate content of the beach sands is found, generally, to increase with increasing distance from the mouth of the Nile River at Rosetta, until a content of about 99.4 per cent is reached westward near Mersa Matruh (fig. 7). In this part of the beach the calcium carbonate is mainly due to the granular carbonate sands. In the middle part of the beach around Alexandria the calcium carbonate is represented by shell fragments. Near the mouth of the Nile River the shell fragments are not very common and quartz sands are dominant.

The relation of the sorting factor to the median diameter is shown in fig. 8. Although the number of samples is rather small, it is clear from the shape of the two curves that, in the case of the "oolitic" carbonate sands, the sorting factor varies very little with the change in the median diameter. This may be interpreted to mean uniformity in the composition of the carbonate sands as pure calcium carbonate. This composition may be contrasted with that of the beach sands east of Dichkeila, where admixtures of quartz grains and different shell fragments are dominant. The trend of the curve indicates that these sands are better sorted the finer they are (up to a size limit of 0.25 mm).

ORIGIN OF THE CARBONATE BEACH SANDS

The age of the carbonate "oolitic" beach sands and limestone along the Egyptian Mediterranean Coast to the west of Dichkeila, ranges from Pleistocene to Recent. In as much as no studies have yet been made on the saturation conditions of the sea water and its variation with temperature fluctuations during the year (small as these are), little can be said about the genesis of the so-

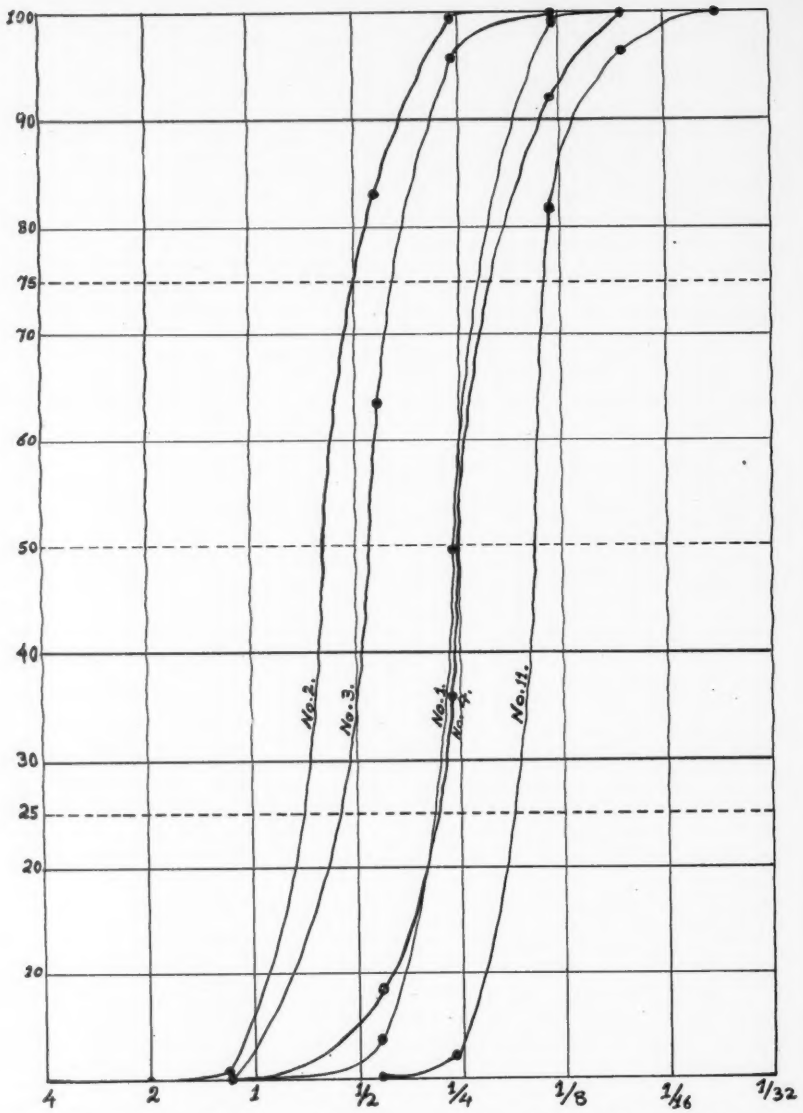

FIG. 4.—Cumulative curves of Mediterranean beach sands; Nos. 1, 2, 3, 4, and 11.

called "oolites" through direct precipitation from sea water. Yet, from the absence of these rounded carbonate sands in the beach east of Dichkeila and from

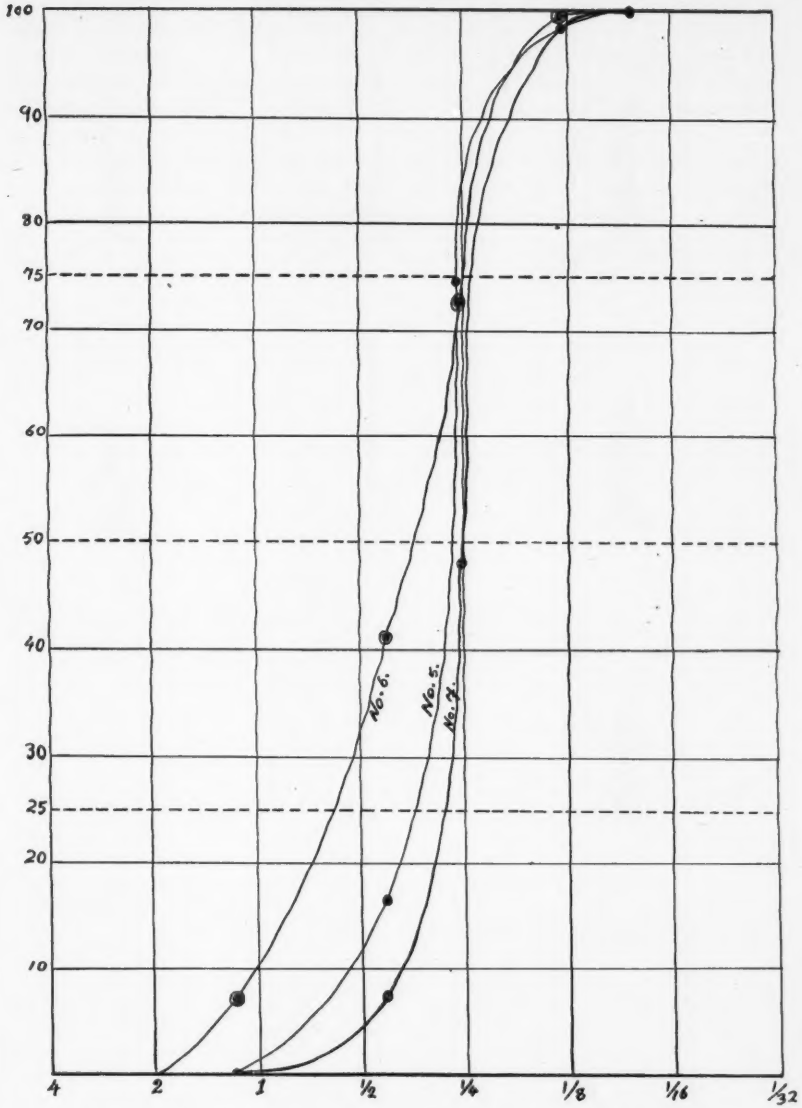

FIG. 5.—Cumulative curves of Mediterranean beach sands; Nos. 5, 6, and 7.

their occurrence to the west of Dichkeila and their gradual change into fairly consolidated "oolitic" limestone ridges away from the sea water (these ridges

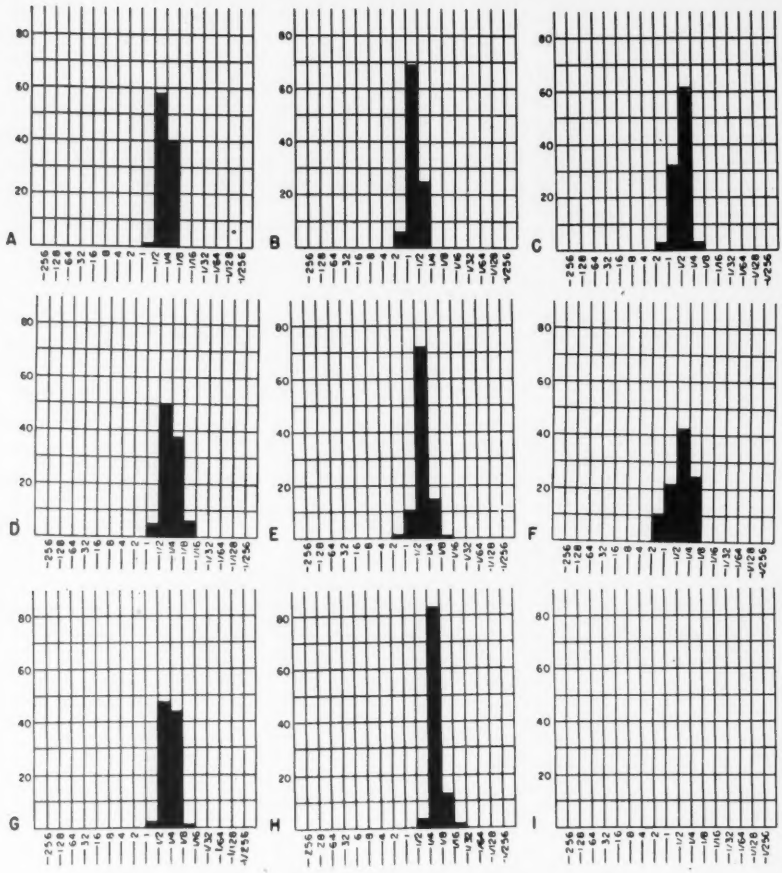

FIG. 6.—Histograms of beach sands from the Mediterranean Coast of Egypt. A. Mersa Matruh; B. Burg el Arab; C. Amria; D. Dichkeila; E. Alexandria, Shatbi; F. Alexandria, Sidi Bishr; G. Edku; H. Rosetta sand dune close to the beach for comparison.

extend down to a depth of about 43 meters below the present sea level), from the pure calcium carbonate composition of these carbonate sands, the shape of the grains (usually irregular, ellipsoidal, rod-like or elongated but not exactly spherical), the absence of nuclei in the so-called "oolites" and the rather rare concentric texture in thin sections, the fairly uniform size of the carbonate grains, the presence of highly polished and well-rounded Tertiary microfossils and the absence of macrofossils, the author is inclined to believe that these carbonate sands are not true oolites and that they represent wind-borne clastic carbonate sands. They are not, therefore, authigenic. These fragmental sands

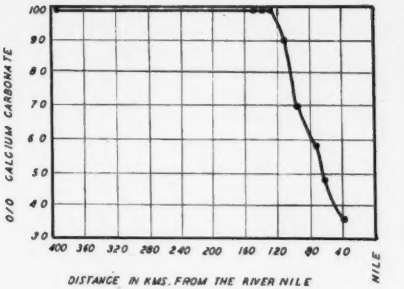

FIG. 7.—Relation between $CaCO_3$ and distance from the Nile.

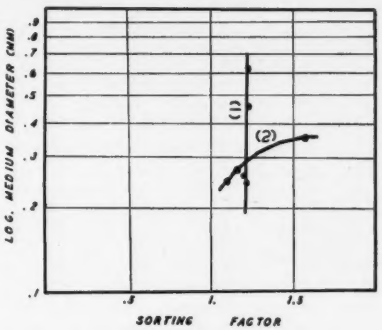

FIG. 8.—Interrelation of the sorting factor with the median diameter. (1) Oolitic limestone. (2) Beach sands east of Dichkeila.

have their origin in the Cretaceous-Eocene limestone formations of the nearby Western Desert. Ball's view (1939) that these carbonate sands were deposited in some sort of a littoral dune formation, now represented by the consolidated limestone ridges mentioned previously, is supported. From their well-rounded character it is considered that these wind-borne sands have been reworked by the agitated nature of the sea waves. The high polish is probably in part an inherited characteristic from the desert environment in the area of the source rock. Carbonate sands away from the sea water are commonly indurated and under the microscope show cementation by a finely crystalline mosaic of secondary calcium carbonate (probably calcite).

True oolites have been described by Eardley (1938) from along the shore of the Great Salt Lake. Precipitation and crystallization of carbonate material in concentric and radial arrangement about a nucleus took place in the agitated saline waters of the lake. The following is a summary of the characteristics of the oolites as described by Eardley (1938): 1) Oolites are found only along the shore lines and form a zone extending to a depth of 3 to 12 feet. 2) Oolites consist of two parts, nucleus and concentric layers about the nucleus. The nuclei consist of mineral particles, chief of which are quartz, and the rod-shaped forms of the faecal pellets of the brine shrimp *Artemia gracilis*. 3) The size of the oolites depends on the size of the nucleus, the number of concentric layers, and the thickness of the layers. 4) The concentric layers consist of about 84 per cent of $CaCO_3$, 5.5 per cent of $2MgCO_3 \cdot CaCO_3$, and 5.6 per cent of very fine clay.

It is, therefore, clear that the so-called "oolites" of the Egyptian Mediterranean beach do not show an exact similarity in character and mode of origin to the true authigenic oolites. Because of this superficial similarity to the true oolites it is proposed to call these highly polished and well-rounded carbonate sands "pseudo-oolites."

MINERALOGY OF THE BEACH SANDS

The samples of beach sands were subjected to dry sieving and the fraction resting on the 120 mesh screen was separated into light and heavy fractions by means of bromoform. The light fraction was found to be composed dominantly of quartz, shell fragments, muscovite, and feldspar.

The following minerals, arranged in a generalized order of decreasing abundance, were identified in the heavy fraction: iron ores (including magnetite and ilmenite); amphiboles (represented

mostly by dark green hornblende); pyroxenes, commonly represented by augite (brownish variety common, dirty yellowish green and titaniferous pink varieties are present), diopside, little aegerite and enstatite; epidote (pistachio-green variety common); garnet (colorless and pink varieties); tourmaline (blue, green, and grayish brown varieties; biotite; zircon; rutile (brookite variety present); monazite; kyanite; staurolite; apatite; spinel; olivine (?); and zoisite. A few calcite grains were observed. Iron ores, amphiboles, and pyroxenes form about 90 per cent of the whole fraction of heavy minerals.

A similar mineral suite with little difference in the frequency of occurrence of some species has been identified by Shukri (1945) in his study of the Nile sediments near Cairo. Shukri has also reported the preponderance of pyroxenes, iron ores, and amphiboles (more than 90 per cent) over the other heavy minerals. Thus the mineral suite of the beach sands is most likely to have been derived, for the most part, from the volcanic highland of Abyssinia (trachytes and basic rocks common; Grubenmann, 1896). Having been carried by the Nile River for a distance of approximately 4000 kilometers, the mineral assortment has received minor additions from other rocks along the course of the Nile; e.g., pre-Cambrian gneisses, schists, granites, and syenites in the cataract regions of the Sudan and Upper Egypt. It is interesting to note that in spite of the long distance of transportation, the amphiboles and pyroxenes regarded as metastable have still persisted.

It is interesting to note, also, that the heavy minerals decrease in concentration as one goes away from the Nile River mouth near Rosetta toward the western part of the coast at Mersa Matruh. The heavy mineral concentration is nearly the same in the whole part of the coast between Rosetta and Alexandria. The beach sands west of Dichkeila to Mersa Matruh, however, are mostly composed of cryptocrystalline calcium carbonate in the "pseudo-oolites," described above, plus a very minor amount of fine quartz. In a whole mount of the heavy minerals from Mersa Matruh beach sands only three grains of a green hornblende, two of tourmaline, and one of a grayish brown augite were observed. This pattern of concentration is significant in that it shows that the sands carried by the Nile River are not distributed along the beach farther west than Dichkeila. Another point of interest is the concentration of the heavy minerals garnet, zircon, monazite, magnetite, and ilmenite in the black sands of Rosetta near the mouth of the Nile. These minerals are now collected and electromagnetically separated by the Anglo-Egyptian Mining Co. Monazite is not concentrated in any of the other sites of sampling. It is possible that selective transportation by sea water enriches wave-formed heavy concentrates and may in itself form heavy concentrates like these black sands of Rosetta. Apparently a great part of the solid material carried in suspension by the Nile River has been dumped along the Mediterranean Coast close to the mouth of the river. Through the action of sea waves and currents the rest of the solid material has been distributed along the length of the coast farther west. Shores away from the mouth are likely to get lesser contributions from the Nile sediments than those close to it. However, detailed investigation of the

EXPLANATION OF PLATE 1

A—Thin-section of "pseudo-oolitic" carbonate sands from Burg el Arab. Plane polarized light, ×50.
B—"Pseudo-oolitic" carbonate sands from Burg el Arab. Reflected light, ×10.
C—Quartz grains left after dissolving the carbonate sands with HCl. Under crossed nicols, ×50.
D—Monazite from the black sands of Rosetta. Plane polarized light, ×25.
E—Zircon (Z), iron ores (O), and epidote (E), from Alexandria. Plane polarized light, ×25.
F—Tourmaline (T), from Dichkeila. Plane polarized light, ×25.

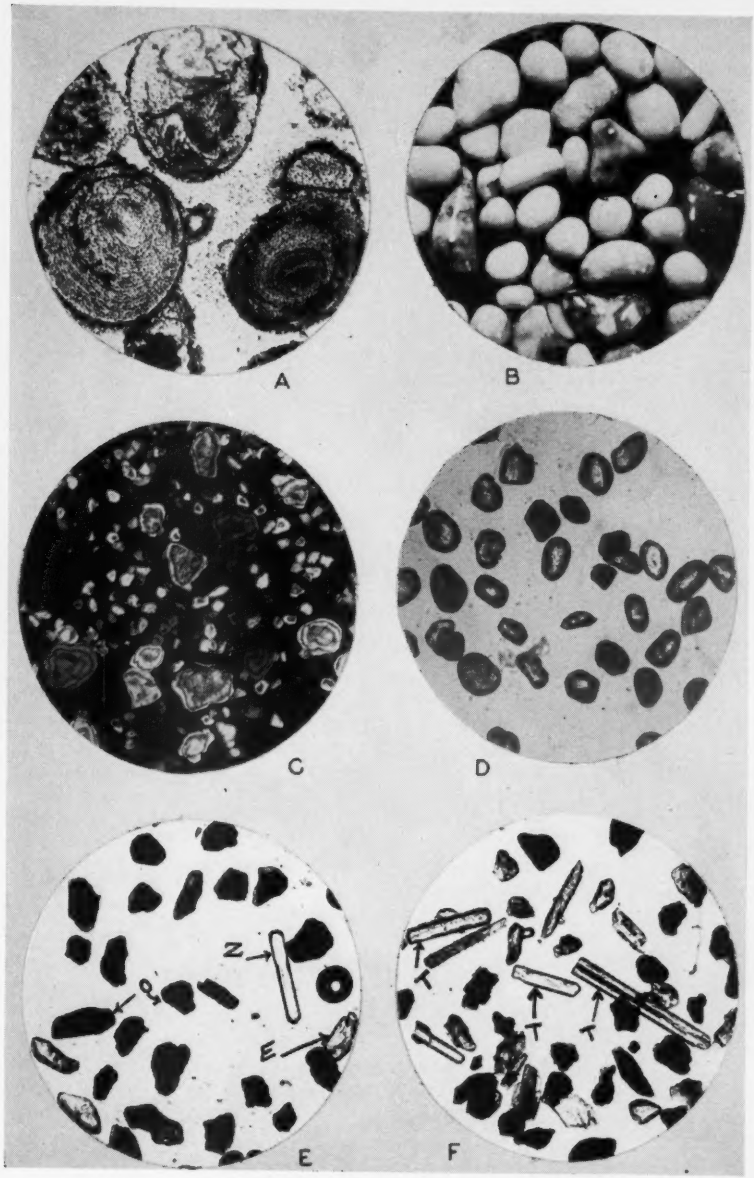

PLATE 1

environmental factors leading to such types of local concentration of the heavy minerals is postponed to a later work.

ACKNOWLEDGMENT

The author expresses his thanks to his friend and colleague Mr. A. M. Y. Khalil of the Anglo-Egyptian Mining Co., Alexandria, Egypt, for furnishing him with samples of garnet, monazite, zircon, magnetite, and ilmenite separated from the black sands of Rosetta.

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Discussion

FURTHER DISCUSSION ON "WHAT IS 'SEDIMENTOLOGY'?"

After considering the interesting discussion *What Is Sedimentology?* which appeared in the June, 1950, issue, I would like to offer the following suggestions:

Two nouns are involved in the discussion: (1) sedimentation, (2) sedimentology. There should be no controversy over these two because both belong to the student of sediments. There need be only an understanding of the meaning of each; their adjustment of relationship to one another then will follow naturally.

"Sedimentation," through the construction of its root and suffix, is a noun of action or act of doing. Geologically it means the act or process of depositing sediment, and without needlessly changing the prior accepted definitions of the two parts of the word it can mean nothing else. When, through the growth of knowledge, additional terminology is needed and a proper word can be constructed from accepted parts, there is no justification in giving additional and, therefore, ambiguous meanings to other parts. Such unjustified, incorrect usage occurs when "sedimentation" is expanded to include all the technology becoming associated with the study of sediments.

The parts with which such a word can be formed are existing. They are *sediment* (broadly meaning *material deposited*) and *-ology* (which equals *-logy*, a combining form denoting *a science or branch of knowledge*). "Sedimentology," thus formed, encompasses not only the material itself and its deposition, but also its genesis, transportation, and diagenesis; the geochemistry, physics, and statistics applicable to its existence; its economic aspects and control; and, so very important, the accurate interpretation of all this knowledge so the sediment may be viewed in its proper perspective within the broad field of natural science.

Geological sedimentology is the most important quantitatively, but industrial and engineering sedimentology must be recognized both for their qualitative consequences upon man's activities and their contribution of technological methods to geology.

Mr. Goldman's call for the assertion of sedimentary petrology's equality with igneous and metamorphic petrology is well founded. As petrology *absolutus*, that of the sediments should lead in technology and understanding because, as Mr. Goldman pointed out, the material for it is so much more accessible to study.

Perhaps it does not so lead because geologists generally have limited the approach to examining *per se* the sedimentary material (sedimentary petrography and petrology) and its deposition (sedimentation), without including all the organized knowledge applicable to the sediment, without understanding the science of the sediment, and without a background of sedimentology instead only of sedimentation.

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REVIEWS

Relations entre la Constitution et la Genèse des Roches Sédimentaires argileuses by Georges Millot. "Géologie Appliquée et Prospection Minière," vol. II, nos. 2–4, 352 pp., 7 plates. Nancy, 1949.

This book is one of the most important contributions to clay mineralogy and the petrology of argillaceous sediments that has appeared in many years.

A series of over sixty samples of argillaceous sediments were collected, mainly from the Mesozoic and Tertiary of eastern France, from beds whose genesis is reasonably well established on the basis of paleontologic, stratigraphic, and other evidence. The complete mineral composition and texture of each of these samples were determined by the use of modern X-ray, differential thermal, electron microscopic, and chemical methods. The analytical data are excellent and one has complete confidence in the clay mineral analyses.

Preceding the presentation of the analytical data for the samples investigated, there is a brief but adequate and up-to-date summary of the composition and structure of the clay minerals and the various methods for identifying them in argillaceous sediments.

The central theme of the book is the correlation of the clay mineral data for the sediments analyzed with their conditions of deposition, and many important generalities are brought to light. The author shows, for example, that illite is the dominant clay mineral component of marine argillaceous sediments with kaolinite usually present in a minor role. In lagoonal sediments illite is the dominant constituent and kaolinite tends to be completely absent. Kaolinite is the dominant clay mineral component in lacustrine sediments if the environment is such that water moves through the accumulating sediments, removing alkalies and alkaline earths. In calcareous lacustrine deposits, the clay mineral is illite.

Montmorillonite was an infrequent component of the samples studied by Millot and no general conclusions are reached regarding its origin. Attapulgite was found only in several continental deposits, but the data are too scant to generalize regarding its genesis.

The author considers in much detail the environmental conditions of pH, cation content, leaching, etc., in which the various clay minerals are formed or in which they are stable. It is concluded that a relatively high pH favors the accumulation of material with a relatively high silica to alumina molecular ratio and the development of three-layer lattice clay minerals. In such an environment the presence of Ca^{++} and K^{+} favors the development of illite. (It is likely that high Mg^{++} would favor the development of montmorillonite. R.E.G.) An environment of low pH and, therefore, the general absence of Ca^{++}, K^{+}, and Mg^{++}, favors the formation of kaolinite.

The author concludes his work with a discussion of the cycle of aluminum, sodium, potassium, calcium, and magnesium, particularly from the point of crystal chemistry, from parent igneous rock through changes in weathering to sedimentation and later metamorphism.

RALPH E. GRIM
University of Illinois

Introduction to Theoretical Igneous Petrology, by E. E. Wahlstrom, 565 pp., John Wiley and Sons, Inc., New York, 1950. $6.00.

In reviewing this book it was necessary to keep in mind that the author's attempt was "to bring together between the covers of a small volume the basic facts and ideas of modern igneous petrology in a form that can be comprehended by the average student of geology." In

this attempt Wahlstrom has done a fine job. The work is held to about 350 pages which include many excellent diagrams.

Chapters 2 and 3 deal with phase equilibria and present in a simple but very complete manner the essentials of phase diagrams for many theoretical and actual systems. This material will be most welcomed by the average student. It is believed, however, that considerable space might have been saved if the two chapters had been consolidated. It is not felt that undue complication would have resulted by such combination, but extensive repetition would have been avoided. The additional space created could then have been put to good use in Chapter 4 by extending the valuable material on rock-forming minerals.

The chapter on "The Crust and Interior of the Earth" serves a very useful purpose, because it attempts to place petrology in its proper position relative to geophysics, geochemistry, and other fields of science. The inclusion of tables of data is a good feature, for it enables the student to do a little thinking on his own and particularly at the opportune moment when his interest is aroused.

In the remaining chapters the author attempts to present the fundamental ideas and concepts of petrology of the present decade as well as those of several decades past. At times, however, this treatment is too concise and almost an outline of information with little or no editorial comment.

It is regretted that only seventeen pages are devoted to the subject of granitization. Nevertheless, the author has amassed a bulk of new material which is made available elsewhere only by reading a great number of individual researches. A rather good selection of readings accompanies each chapter. These should prove valuable to the interested student.

It is believed that the last chapter, which deals with rock classification, should have been eliminated because the material is more a matter of petrography. The historical review of rock classifications, though interesting and well done, is somewhat out of place in this text. The appendix is concerned with physical-chemical principles and should prove very helpful to the reader.

The treatment of material is simplified but quite complete. The book fills a long felt need and will meet with great appeal to students in petrology. It will appeal particularly to those who wish to obtain a rapid but fairly complete understanding of the fundamentals of igneous petrology and a survey of some of the classic and recent literature.

Wahlstrom has undertaken a rather bold task of covering such a large field of geology in so brief a treatment.

CARLETON A. CHAPMAN
University of Illinois

Stratigraphy and Sedimentation, by W. C. Krumbein and L. L. Sloss, 507 pages, 123 illustrations, W. H. Freeman and Company San Francisco, Calif., 1951. $5.00.

"It is the purpose of this book to assemble and integrate the facts, principles, and hypotheses bearing upon stratigraphy and sedimentation in a form that may be studied and assimilated in an efficient manner." Fortified by their extensive field, laboratory, and classroom experience the authors have accomplished their stated purpose with commendable clarity, conciseness, completeness, and discrimination.

Reader interest is stimulated and maintained by the orderly arrangement of subject matter and the directness of presentation. Essential concepts and principles are clearly set forth with brief but adequate historical background. The authors have not hesitated to express their own considered opinions regarding controversial questions. Techniques and data gain importance because their utility and applications are stressed.

Progress and expansion have been very rapid in these important fields during recent years as is demonstrated by the hundreds of references listed in the 27 pages of Bibliography. About half of

these references are less than 10 years old. Acquaintance with this material is difficult because it has appeared in so many publications. Krumbein and Sloss have achieved notable success in their avowed purpose to analyze and synthesize this great store of information and concepts. They have thereby rendered an inestimable service to student and professional geologists.

Doubtless the first edition of any text or reference work on such broad fields as stratigraphy and sedimentation will need some subsequent additions and revisions. Some useful terms may have been overlooked and some statements evidently need revision or qualification. For example, the statement that radioactivity logs can be used to distinguish water-bearing beds from oil or gas-bearing beds is not generally supported by field experience. However, so much that is new and essential has been included that minor omissions or doubtful statements are inconsequential by comparison.

The reviewer believes that most readers will find this book more than adequate in its treatment of various major topics to which the 14 chapters are devoted. Generalizations of the introductory chapter are followed by 24 pages concerning the organization and classification of the stratigraphic column, including an excellent summary of terminology and rules of stratigraphic nomenclature. The third chapter (35 pages) deals with Stratigraphic Procedures, both as to outcrop and subsurface studies, preparation of columnar and cross sections, various logging techniques, and presentation of data.

Professor Krumbein's well known critical and constructive work in sedimentation has equipped him to write authoritatively in the next 4 chapters (156 pages) on the Properties of Sedimentary Rocks, Classification and Description of Sedimentary Rocks, Sedimentary Processes and Sedimentary Environments.

Chapter 8, entitled Stratigraphic Paleontology, apparently reflects the extensive work and critical stratigraphic studies and field work of Professor Sloss.

The authors show an appreciation of the importance of sedimentary facies by devoting an entire chapter (34 pages) to discussion and illustrations of this subject. Much emphasis is given to the need of map representations showing facies aspects of a designated stratigraphic unit by interrelated but separate studies dealing with lithology, biology and tectonics.

Chapter 9 on Facies and succeeding chapters on Principles of Correlation, Tectonic Framework of Sedimentation, Sedimentary Tectonics and Stratigraphic Maps are referred to as "Analytical Stratigraphy" in the Introduction.

The final chapter is devoted to "Interpretative Stratigraphy"—"in which the data previously gathered, organized, and analyzed are caused, by interpretation and synthesis, to yield the required information" for the solution of a particular problem or problems. "In chapter 14, broad-scale paleogeography is discussed as an important aspect of stratigraphic interpretation."

The authors have incorporated in this book not only their own important contributions but also many advances in stratigraphy and sedimentation by present and former associates, Professors E. C. Dapples and F. J. Pettijohn. The recent data and concepts of many other contemporaries are given generous recognition and discussion.

M. G. CHENEY
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